Palaeomagnetic studies in the British Caledonides

Thesis

PALAEOMAGNETIC STUDIES IN THE BRITISH CALEDONIDES

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by:-

William Adrian Morris

Department of Earth Sciences

The Open University

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CONTENTS

Chapter 5. A regional palaeomagnetic interpretation

ABSTRACT

In this study a large amount of new palaeomagnetic data ~~is~~ reported from the Paleozoic of the British Isles. The data are consistent with episodic polar shift from the vicinity of 10°N, 180°E in the Ordovician to 0°, 145°E in the Siluro-Devonian and to 25°N, 160°E in the late Devonian-early Carboniferous. The Cambrian pole is less well defined but may have lain near 30°N, 170°E. Each polar shift appears to predate a phase of deformation, i.e. crustal drift and oceanic plate consumption significantly precedes orogenesis and continental plate collision.

Large collections were made from two regions within the British Caledonides; the English Lake District, and the South Mayo Trough. Palaeomagnetic data from the Carrock Fell Gabbro Complex indicate intrusion as a dyke at some time during the Upper Ordovician subject only to slight subsequent tilting. Folding in both the Eycott and Borrowdale Volcanic Groups is found to be essentially simple and complete by the end of the Ordovician. The end-Silurian deformation which many authors have considered 'climactic' produced tight folds only in the high-level Silurian sediments. The stratigraphically lower and more competent lavas were merely tilted and cleaved. A similar sequence of

deformation has affected the rocks of the South Mayo Trough. In this case however, the end-Silurian deformation accompanied major azimuthal rotation and complicated southward thrusting.

A Proto-Atlantic ocean on the site of the present Caledonian orogenic belt has been cited by many authors on a number of separate geological criteria. Palaeomagnetic evidence from the margins of this belt in the British Isles indicates that little (or no) closure has taken place across the Caledonides since early Ordovician time. The available data do however, indicate apparent discrepancies between the Baltic/Russian and North American plates, and a British sub-plate. A number of explanations is ~~are~~ possible:

(1) Euramerica was a rigid plate, hence some of the data are invalid,

(2) the three units of Euramerica were tenuously attached:

geological evidence for postulated plate margins outside Britain is discussed

(3) the present data are inadequate to define a British sub-plate.

In this thesis the third alternative is preferred.

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CHAPTER 1

INTRODUCTION

1.1 The relevance of palaeomagnetism to study of the Caledonides

When a continental margin collides with an island arc, or another continental margin, an orogenic zone is produced (DEWEY and BIRD 1970 a, b). Since all recent orogenic belts can be explained by plate tectonics, it has been assumed by many workers that exactly the same process was active in the geological past (DEWEY 1969, BURKE and DEWEY 1970, see discussion PIPER, BRIDEN and LOMAX 1973). However, much of the evidence used to recognise distinct plate margin types is transitory e.g. high heat flow, seismically defined Benioff zones, or magnetic strip anomalies. It is usually the secondary products of these mechanisms which are sought in the geological past e.g. metamorphic zonation, K-Ar age zonation, thrust sheets and fault zones. As the geological record is always incomplete, a wide range of evidence is required before individual regions can be allotted to distinct plate margin types.

This thesis is concerned with the plate tectonic evolution of the Caledonian orogenic belt. This major fold belt of mid-Palaeozoic age trends NE-SW across most of the northern part of Great Britain. Most of the rocks are deep water marine sediments bordered by shallow water shelf deposits. Some of the volcanic rocks from the belt have been compared to present day ocean floor material. Geological evidence of various kinds has been cited in support of a major Proto-Atlantic ocean on the site of this orogenic belt e.g. Ordovician faunal distributions (WILSON 1966, WILLIAMS 1969), regional variations of vulcanicity, sedimentology and deformation (DEWEY 1969), Ordovician ophiolite complexes (BIRD, DEWEY and KIDD 1971), petrochemical variations of Ordovician volcanics (FITTON and HUGHES 1970), K-Ar age distributions (DEWEY and PANKHURST 1970). None of this information provides a quantitative estimate for the size of this proposed ocean. Moreover, the position and number of plate boundaries, and the details of individual plate motions remain debateable (DEWEY 1969, FITTON and HUGHES 1970, BAKER 1973, GARSON and PLANT 1973, GUNN 1973).

Palaeomagnetism provides evidence for the latitude and orientation of individual rock units at the time of rock formation. Therefore contemporaneous rocks from the same plate should show the same smooth systematic variation of inclination with latitude, as does the present geomagnetic field. Assuming a geocentric dipole model all stratigraphically equivalent rock units should yield the same palaeomagnetic pole position. However for contemporaneous rocks from different plates, the separation of the calculated palaeomagnetic pole positions provides a quantitative measure of the distance between the two plates for the instant under consideration. Data from a particular region are usually summarized by plotting polar variation as a function of time (polar paths). The duration of the individuality of two regions can then be discussed in terms of the separation of their two polar paths. At the junction where two plates are colliding, complicated tectonic thrusting and rotations may be taking place, as the continental material attempts to override the down-going plate. A measure of these rotations is provided by the separation of contemporaneous pole positions from within the same plate.

Hence, by analysing a large amount of data collected over the areal extent and duration of the Caledonian orogeny, palaeomagnetism provides a means of establishing tectonic history on both a regional and a local scale. In this thesis, the approach has been to cover the greatest possible stratigraphic range and the largest areal extent in the time available. Inevitably this has meant that little time was given to the back up rock magnetic studies commonly associated with palaeomagnetic investigations, hence in most cases the composition and texture of the remanence carrying phases has not been identified. The ages of the stable remanences of the rocks studied have been established, by utilising certain aspects of their well known geological histories. In some cases, this was not possible, and it was therefore necessary to rely on the proven finding from other palaeomagnetic studies of undeformed, unmetamorphosed rocks that the stable remanence gives a spot reading of the ambient geomagnetic field at the time of rock formation.

This work forms part of a major investigation into Caledonian palaeomagnetism by the Leeds palaeomagnetic research group. At the beginning of the project, remanence data from the Cambro-Ordovician of the British Isles was sparse. CREER (1957) had published a result from the Caerfai Series, but because the inferred pole fell close to the relatively well established Carboniferous pole position, its validity was doubted. NESBITT (1967) had reported results from the Ballantrae

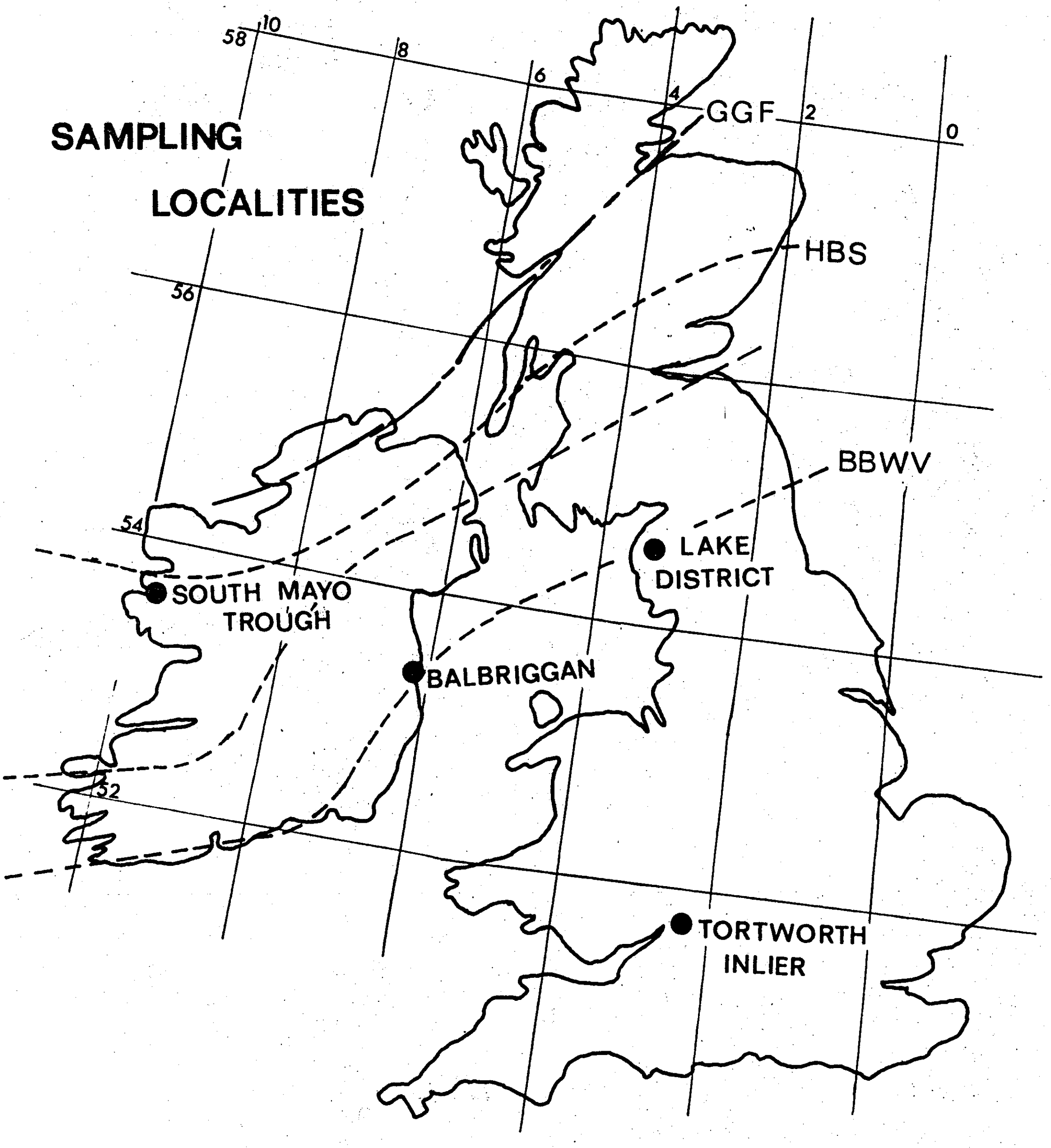


Figure 1.1 Sampling localities

GGF. - Great Glen Fault, HBS. - Highland Boundary Suture

BBWV. - Borrowdale -Balbriggan - Waterford Volcanics

(Dewey 1969)

Volcanics, the Eycott Group, and the Builth Volcanic Series, but because of the small number of samples, these collections merely indicated their suitability for palaeomagnetic study. A result from the Mweelrea ignimbrites, western Eire, (DEUTSCH 1969) was considered to be anomalous. Siluro-Devonian data was more plentiful, but a controversy had developed over its detailed interpretation. In this thesis, major studies of Ordovician and Silurian material were made from two regions; the English Lake District (Chapter 2), and Counties Mayo and Galway, Eire (Chapter 3). To extend the areal coverage a number of miscellaneous collections were made (Chapter 4). Finally, in the light of these new data the various plate tectonic models are discussed (Chapter 5).

1.2 Palaeomagnetic Methods

In any palaeomagnetic enquiry the basic requirement is to establish the syngenetic remanence of the material under investigation. Standard sampling and measurement techniques were employed throughout (IRVING 1964, COLLINSON *et al*. 1967 McELHINNY 1973). No new procedures have been introduced in the present work. Therefore, only brief outlines are given of the methods used and the nomenclature employed in this thesis (Table 1.1).

Two methods of field sampling are used; field drilling and block sampling. In general, field drilling is preferred as greater orientation accuracy is possible. Cores are usually oriented before being detached from the host rock. Inclination is measured by clinometer, while bearings are given by sun-compass, magnetic compass, or long-sight, Specimens were cut into cores 2.5 cm. dia. by 2.5 cm. long. Remanence measurements were made on a PAR SM2-D spinner magnetometer. Strongly magnetized specimens ($>1 \times 10^{-4}$G) were spun in three orthogonal positions, which with a two channel phase sensitive detector means that the individual cartesian components are the mean of two readings. For weaker specimens six pairs of measurements were made, individual components being the mean of four readings.

To interpret any remanence direction it is essential to establish its age. Geological evidence can assist this, where, for example, simple folds, conglomerates, or igneous contacts can be sampled. It is assumed that remanence in the rocks is imposed parallel to the local ambient geomagnetic field at the time of rock formation. If the ambient field changes, then the less stable remanence components may follow. This effect builds up with time (VRM), gradually affecting higher coercivity (critical blocking temperature) components. Laboratory cleaning techniques have the effect of progressively removing these successively 'magnetically harder' components (McELHINNY 1966, STEPHENSON 1967). The stable remanence is taken as the level at which the remanence vector exhibits the least change during successive demagnetization steps (using the Stability Index of BRIDEN (1972)).

In this thesis a 'site' is defined as providing a spot reading of the local geomagnetic field, e.g. a single lava flow, or a sedimentary horizon. A 'sample' corresponds to each oriented block (or core), a number of 'specimens' are cut from each sample. If the remanence direction of each specimen is represented by a unit vector, then the sample mean is the vector sum of the individual directions, and so on in an hierarchical system. A measure of the 'tightness' of grouping of these directions is provided by Fisher's (1953) analysis, which is dependent upon the observed remanence directions conforming to a prescribed Fisherian distribution with a given probability (usually p = 0.05)

A number of significance tests have been based on this distribution, and these are normally applied to quantify field stability criteria (WATSON 1956, a, b, McELHINNY 1964, COX 1969). WATSON and IRVING (1957) have shown that under certain conditions it is possible to separate within -, and between - site precision; a more sophisticated analysis which has been used in this work wherever appropriate.

These techniques are adequate for full statistical studies within the same plate. However for the comparison of data from different plates it is necessary to allow for any subsequent relative rotations of those plates. This is achieved by the method of Eulerian rotations (BULLARD, EVERETT and SMITH 1965). A convenient computer programme (THOMAS personal communication 1973) was available for this purpose.

CHAPTER 2

THE ENGLISH LAKE DISTRICT

2.1. Introduction

The English Lake District, a Lower Palaeozoic Inlier, includes igneous rocks that are relatively undeformed in comparison with rocks of the main Caledonian geosynclinal belt within which it lies. The inlier is basically a broad anticline with Cambro-Ordovician Skiddaw Slates in the core (Figure 2.1).

On the southerly and more gently dipping limb, the Slates are overlain by well over 4000m. of acid and intermediate lavas and pyroclastics, referred to the Borrowdale Volcanic Group. These in turn are capped by late Ordovician and Silurian sediments. By contrast on the northern limb of the major structure the volcanics are much thinner (~2500m.), dip more steeply, and are referred to as the Eycott Group (DOWNIE and SOPER, 1972). Nowhere is there continuity of outcrop from the southern to the northern limb of the main anticline. DOWNIE and SOPER (1972), NUTT (1968) and WADGE (1972) have shown that the Eycott Group was tilted prior to the eruption of the Borrowdale Volcanic Group. Also the two Groups are chemically distinct, the north is rich in basalts and basaltic andesites with minor rhyolites,

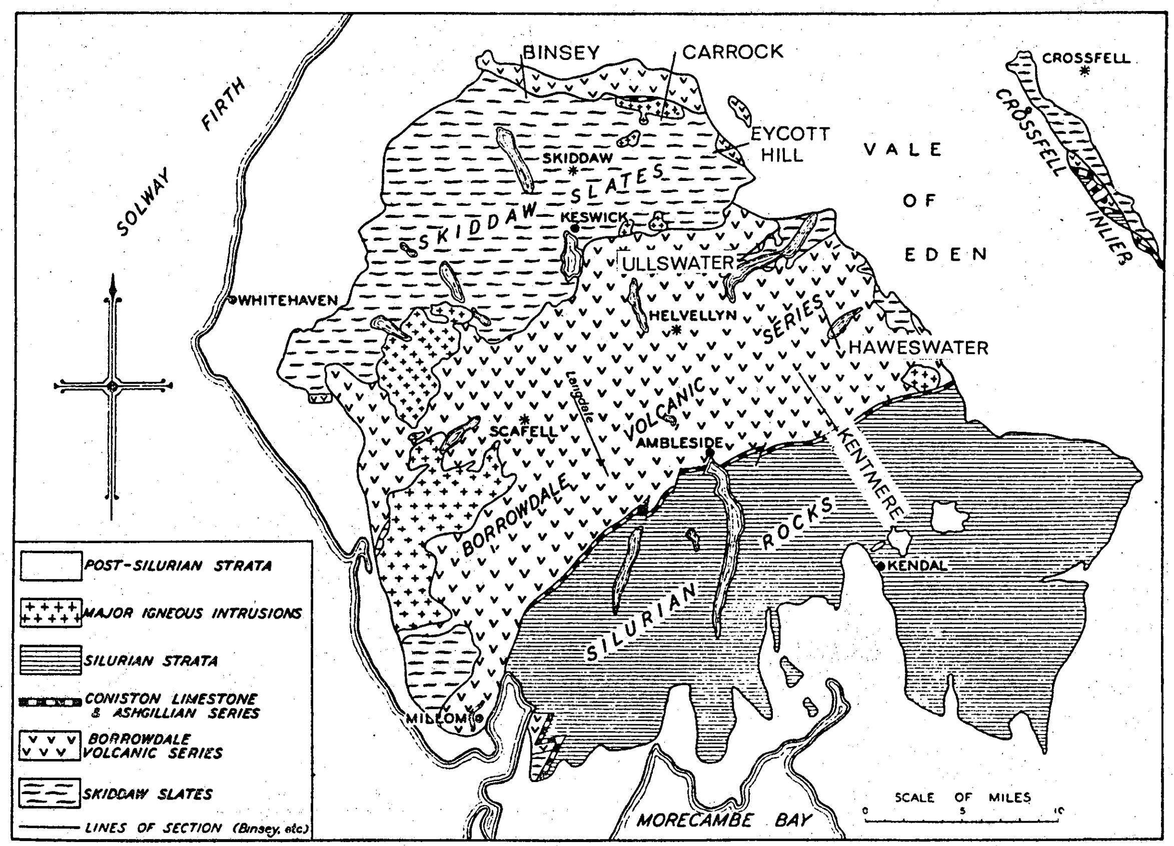


Figure 2.1 Generalised geology of the Lake District

whereas in the southern outcrop, rocks of andesitic and dacitic composition predominate (FITTON and HUGHES, 1970).

The freshness and degree of outcrop of the rocks in the two regions encourages palaeomagnetic study. Moreover, a preliminary investigation by NESBITT (1967) suggested that the rocks from Eycott Hill (Eycott Group) carried a stable remanence, with a direction similar to that in other British Palaeozoic rocks, but neither the sampling nor the stability evidence was adequate to define the local Ordovician geomagnetic field satisfactorily. In this study comprehensive sampling of the Eycott Group was carried out mainly in two sections at Binsey (15 sites) and Eycott Hill (15 sites), between which there is a large change of dip and strike. In the Borrowdale Volcanic Group small collections have been made from Kentmore (4 sites), N.W.Ullswater (14 sites), and Haweswater (7 sites). Both these sets of results are supported by detailed laboratory stability evidence.

The overall simple picture of Lake District geology is complicated by many large and small instrusions. The largest group comprises granites and granodiorites of Caledonian age (i.e. circa 400 m.y), perhaps the most important of these being the Skiddaw

Granite, which has a large metamorphic aureole affecting some of the material reported in this study. There is also an older, more basic, suite of intrusives of which the Carrock Fell Complex is undoubtedly the largest. It was intruded along the Eycott Group/Skiddaw Slate junction close to the area where the Eycott Group lavas were sampled. The present field relationships are illustrated in the simplified geological section (Figure 2.2). The mode and time of intrusion of the Carrock Fell Complex in relation to the folding of its host rocks remains controversial. It will be shown here that palaeomagnetism clarifies the local sequence of igneous and structural events. As well as this major basic intrusion, there are a number of basic dykes and minor intrusions of uncertain age, varying from post-Skiddaw Slates to pre-Coniston Limestone Group. Small collections were made for palaeomagnetic analysis from minor intrusions which outcrop in the regions of Carrock Fell and Kentmere.

The last phase of igneous activity in the Lake District was a series of highly vesicular basaltic lava flows. Near Cockermouth (Eastwood et al. 1968) these lavas can be seen unconformably overlying Skiddaw Slates, while lying comformably on top of them are limestones of basal Carboniferous age. Five sites were collected from the four flows which are topographically expressed as terraces near Wood Hall, Cockermouth.

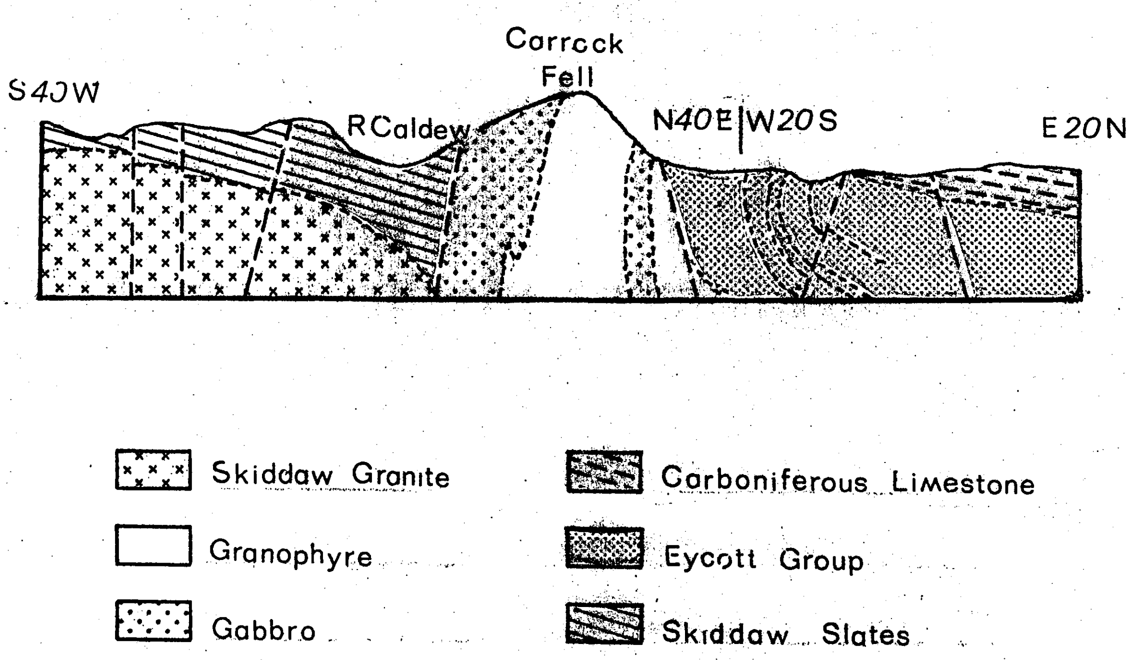


Figure 2.2   Sketch section of the Carrock Fell Complex

2.2 The Eycott Group

2.2.1 Introduction

The earliest report on the 'Northern' area of Borrowdale Volcanics was by WARD (1877) under the title 'Lower Silurian lavas of Eycott Hill'. More recently the area has been comprehensively mapped by the (then) Geological Survey (Eastwood et al 1968). Current geological interest in the region is concerned mainly with its detailed structural evolution.

The sequence consists of lavas, ashes, tuffs and agglomerates, ranging in composition from rhyolite to olivine-basalt, although the lavas are predominantly andesitic and the pyroclastics mainly acid~~s~~ic. The lavas are generally aphyric, but a distinctive plagioclase-phyric variety with phenocrysts up to 2mm long - 'Eycott-type' lava of Eastwood et al. (1968) - occurs at various stratigraphic levels. Its occurrence eases the problem of correlation between the principal outcrop sections.

The series is divided into two groups, the Lower (Binsey) Group and the Upper (High Ireby) Group. DOWNIE and SOPER (1972) have suggested that these units should more properly be termed 'Formations' and have proposed the name 'Eycott Group' to supercede the more vague 'Northern" Borrowdale Volcanics. This convention is followed henceforth. The Binsey Formation is best developed in the west of the area notably on Binsey (Figure 2.3 (a) and (c)), where it attains its maximum thickness of 1190 m. The lowest beds are Eycott-type lavas (sites 25, 26) interbedded with mudstones and slates which are regarded as of _Didymograptus bifidus_ age by EASTWOOD _et al_. (1968) - a correlation confirmed by the micropalaeontological data of DOWNIE and SOPER (1972). Ten sites in all were sampled in this type-section, of which nine are within a single fault block. Site 25 lies in an adjacent fault-block and continuity with the main section is not proven; but it will be shown later that our palaeomagnetic results do not suggest any substantial age difference. The sequence thins drastically between Binsey and Eycott Hill so that, at the latter, the Binsey Formation is only 120m. thick. Five more sites were collected at Eycott Hill. At this locality the oldest volcanic horizon (below site 1, Figure 2.3b) is a red and green mottled tuff which corresponds to the level of site 34 on the upper southern slopes of Binsey. The base of the Eycott Group in the Binsey-Eycott area almost certainly falls in the _D. bifidus_ zone, but is probably slightly younger within this zone on the eastern part of this area (SOPER, personal communication, 1972).

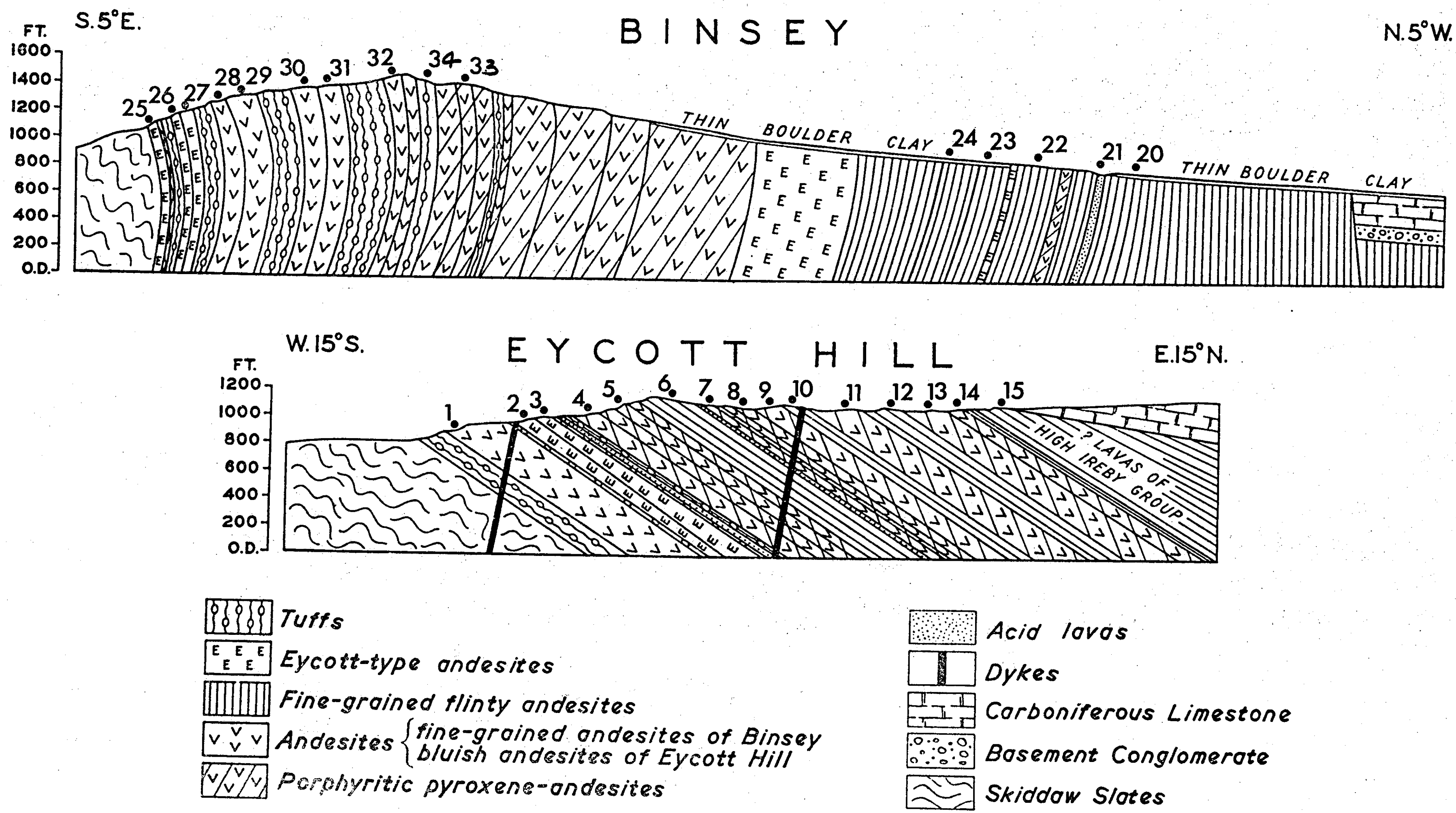


Figure 2.3(a) Geological sections across Binsey and Eycott Hill

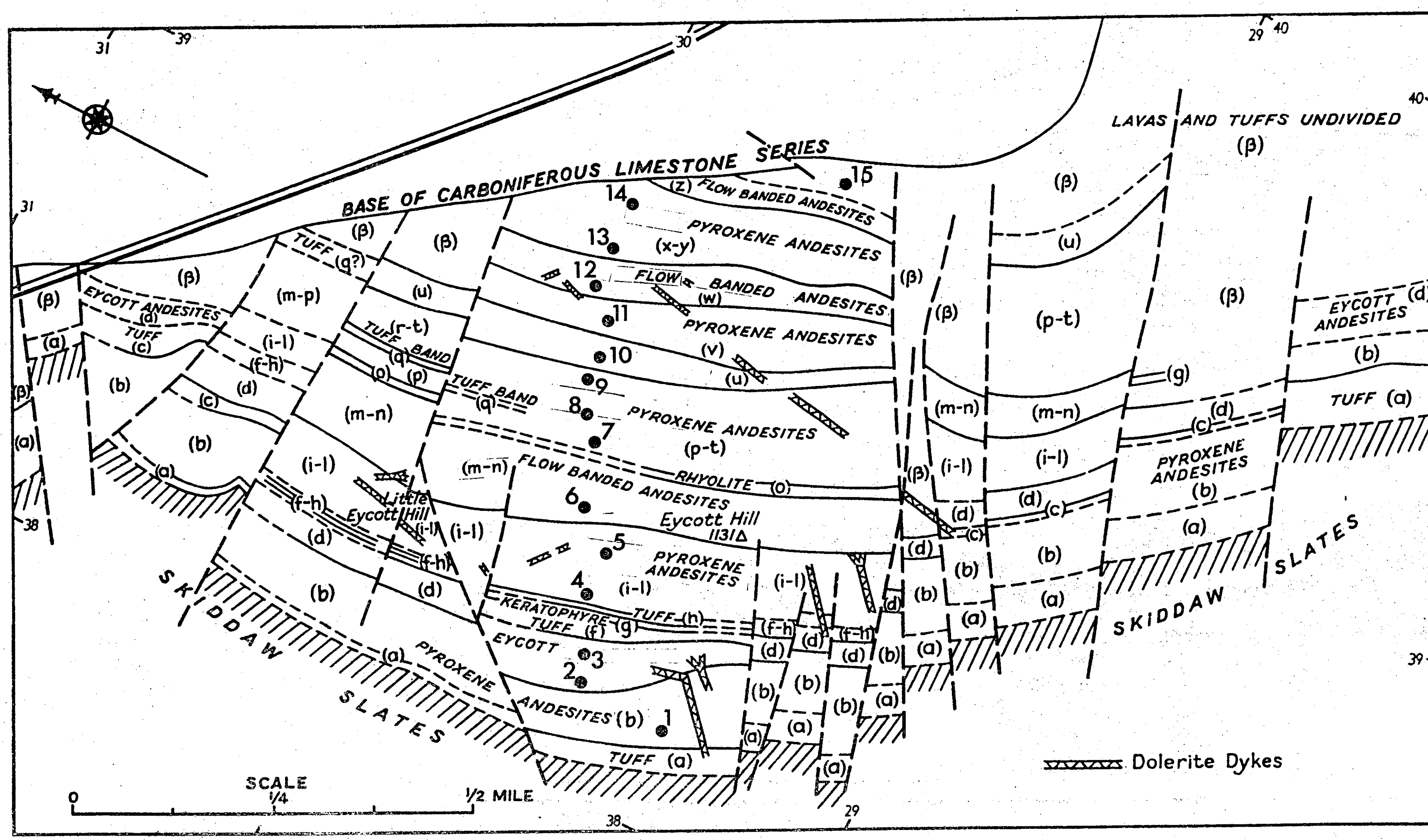


Figure 2.3(b) Geology and sampling localities - Eycott Hill

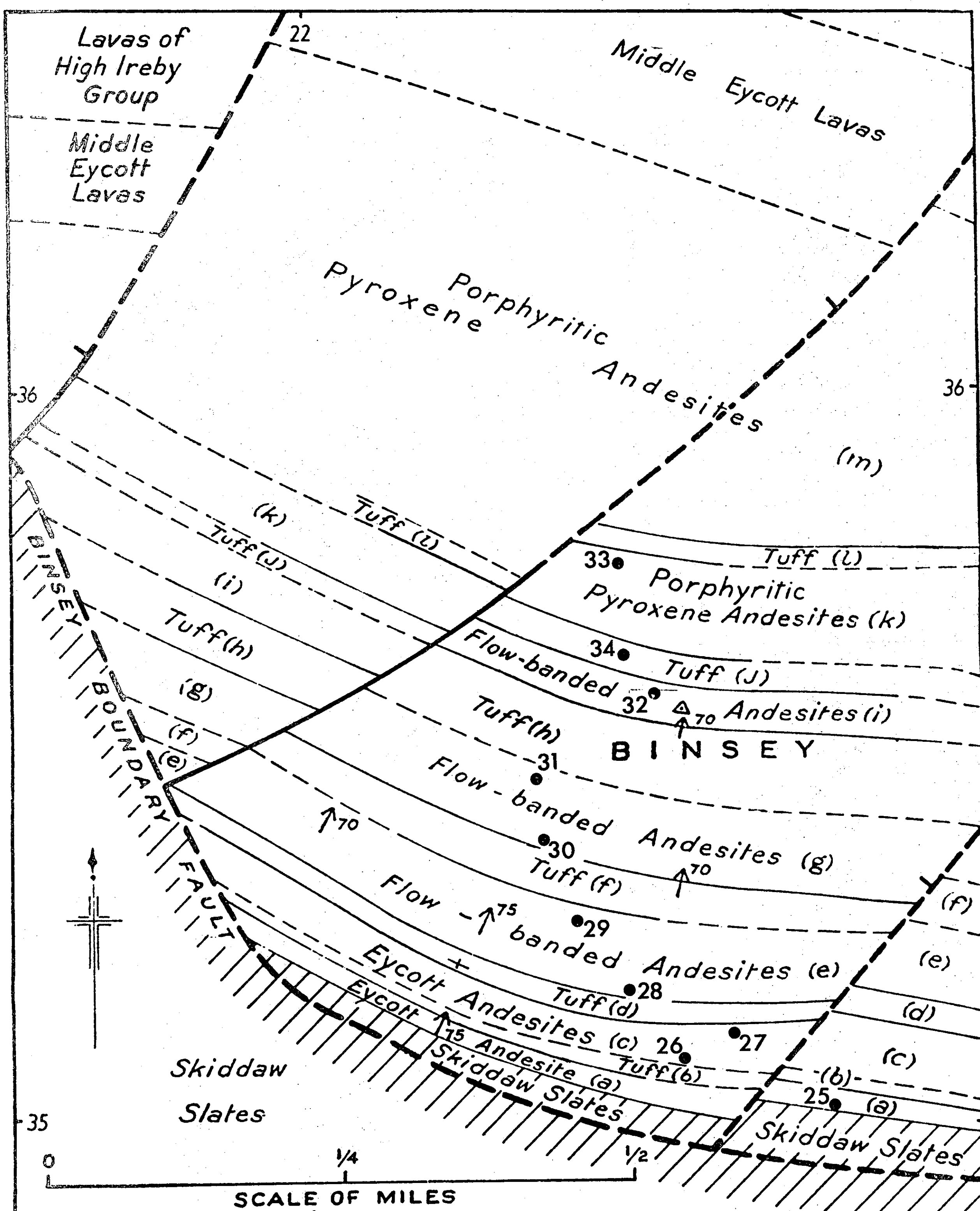


Figure 2.3(c) Geology and sampling localities - Binsey

The base of the High Ireby Formation is marked everywhere by several flows of Eycott-type lava. As with the Binsey Formation, its maximum development is near Binsey where it reaches about 1200m. However on the line of section sampled at Binsey only the top 200m are exposed (five sites, Figure 2.3); the intervening 1000m. to the top of the High Ireby Formation being drift covered. At Eycott Hill the High Ireby Formation is only 600m. thick but is well exposed throughout as a result of stong glacial action. It is possible to distinguish separate lava flows of which ten were sampled. Two sites (flows) were also collected from an isolated outcrop of High Ireby Formation near Linewath. Together these probably help to fill the gap in the record due to lack of exposure at Binsey.

The eastward thinning of the Eycott Group can be demonstrated in each of the major stratigraphic subdivisions. Absolute thicknesses for the High Ireby Formation, however, are additionally influenced by the overlap of the Carboniferous Limestone which terminates the Lower Palaeozoic outcrop at different stratigraphic levels along the angular unconformity.

In the main section at Binsey the lavas dip steeply N at 70° while at the isolated site 25 the dip is only 30°. At Eycott Hill the sequence dips ENE at 38°. This difference in attitude between the two areas facilitates a fold test of the age of remanence.

All collecting was by portable field drill and orientation by sun and/or magnetic compass and clinometer.

2.2.2 Results from the Binsey Formation

Total NRMs at 12 of the 15 sites are significant at the 95 per cent probability level (Table 2.1). The three non-significant sites are in very fine grained rocks in which petrological alteration is visible in hand specimen. Ten of the site mean directions after dip correction are grouped around $D = 10^{\circ}$, $I = -45^{\circ}$. The other two are anomalous and relative to their *in situ* position are grouped near the present geomagnetic field. The total NRM intensity ranges from 0.05×10^{-3}G to a maximum of 3.0×10^{-3}G. Progressive a.f. demagnetization was performed on one specimen from each site. The behaviour of the majority of the samples can be categorised into two groups:

(1) little change of direction; regular decrease of intensity; uniform Stability Index (Figure 2.4).

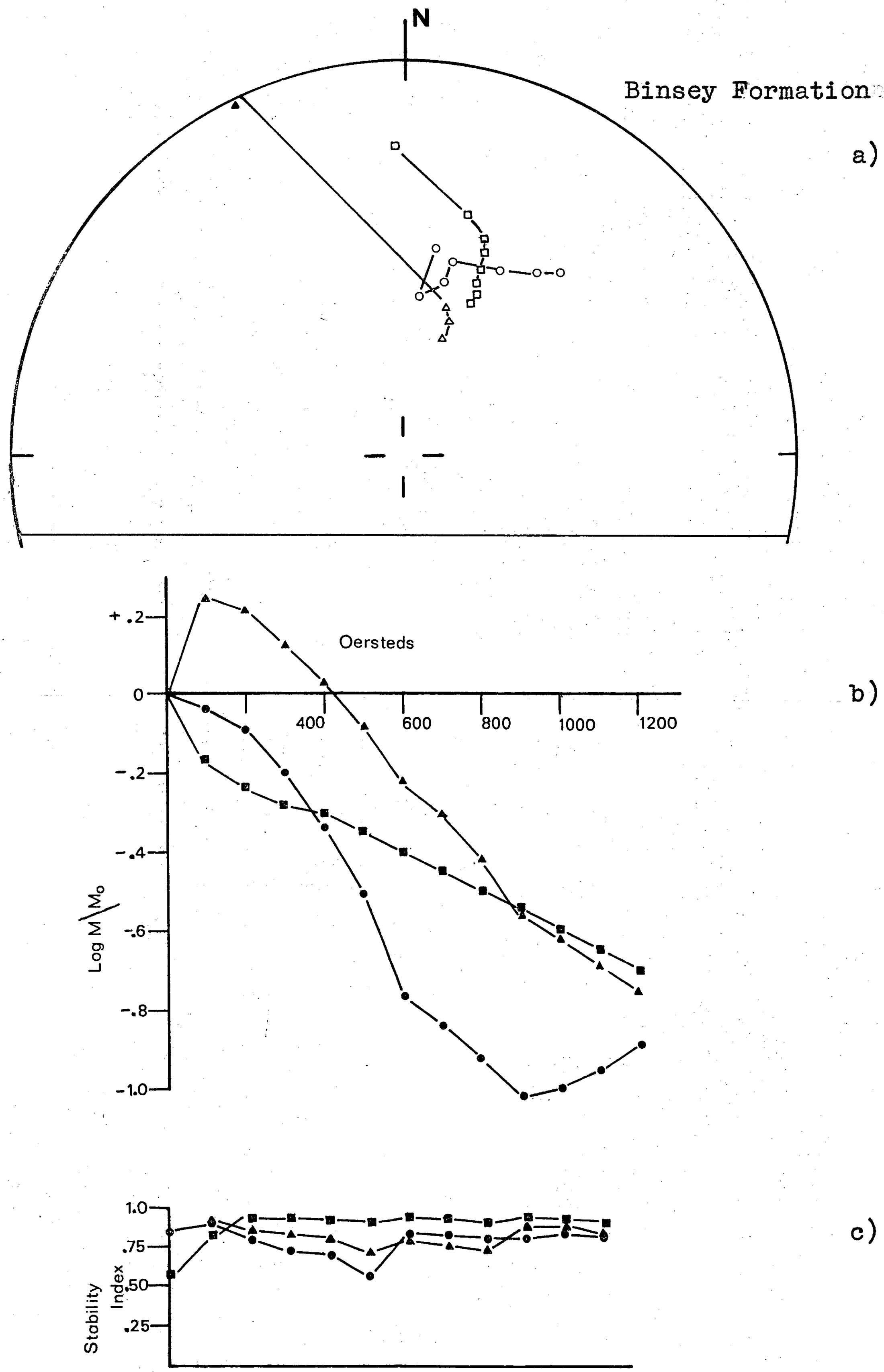


Figure 2.4. Variation of remanence direct ion (a), intensity (b), and Stability Index (c) upon a.f. demagnetization. Equal angle stereographic projection, open symbols indicate negative inclination

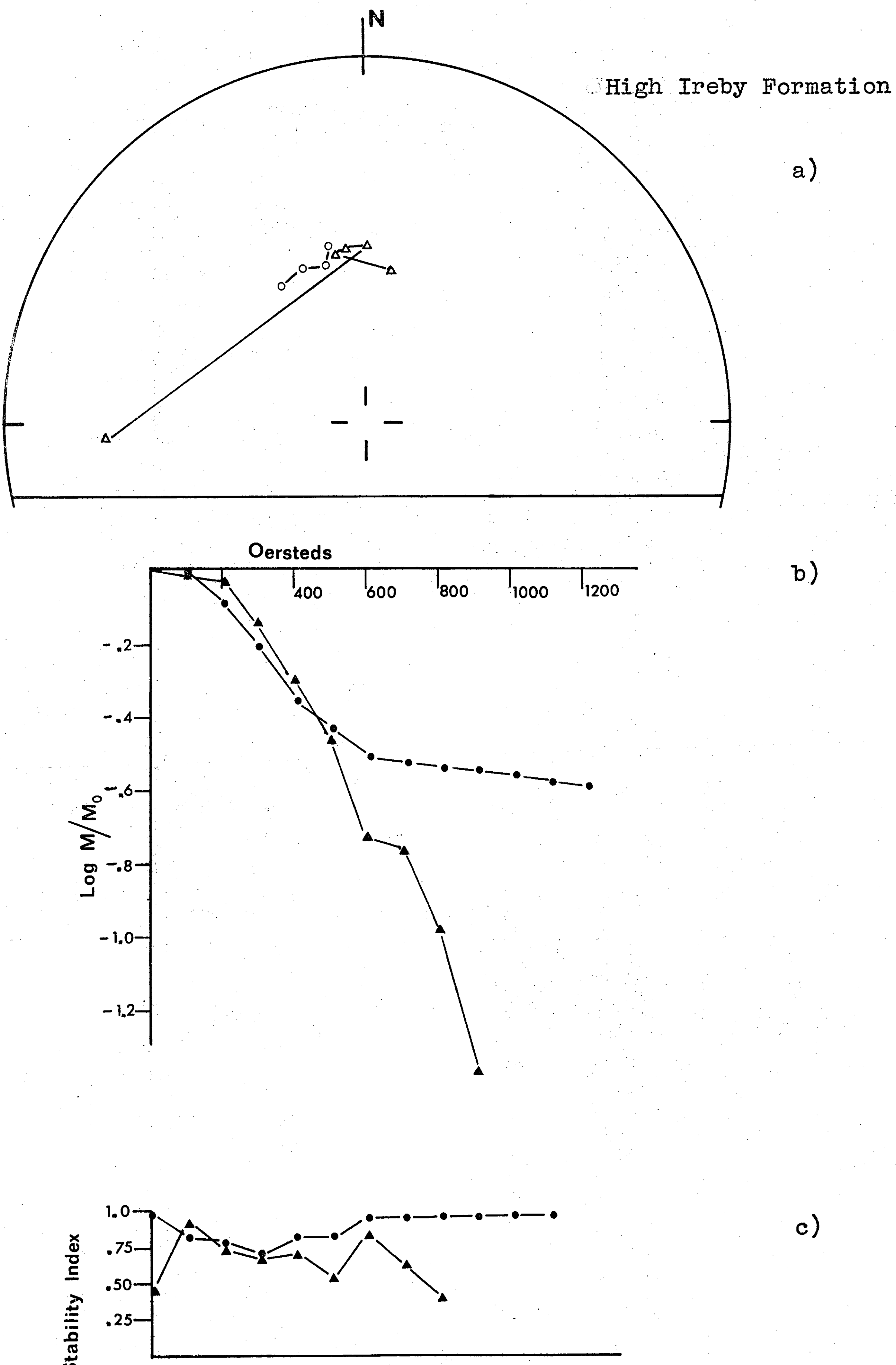


Figure 2.4. Variation of remanence direction (a), intensity (b), and Stability Index (c) upon a.f. demagnetization.

This is identified as a single component remanence with a broad coercivity spectrum.

(2) large change of direction in low alternating fields; large irregular decrease in intensity; and irregular fluctuations of Stability Index (Figure 2.4). This may be the result of a secondary magnetization superimposed upon a stable component with a limited range of coercivities. Figure 2.4 also shows an exceptional demagnetization curve which exhibits a marked increase in intensity (twice NRM) upon 100 Oe treatment. Further treatment produces a gradual decrease of intensity, with constant direction and Stability Index. Hence the initial step removes a weak secondary component of low coercivity.

Optimum fields for a.f. cleaning ranged from 200 Oe to 900 Oe, with five sites being treated at 200 Oe and another five at 700 Oe. After this treatment 14 of the 15 sites were significant (Table 2.2). Two of the previously non-significant sites (3, 27) became significant after cleaning at 900 Oe and 200 Oe respectively. In polished section Site 5, which failed to respond to treatment shows low opaque ore content, and extensive colloidal haematite. Within site grouping improved at 12 of the 14 significant sites; only at sites 30 and 34 did precision decrease, and even there not by a significant amount by the criterion of McELHINNY (1964). The mean directions at sites 1 and 32, which were anomalous before cleaning, now fall within the group centred at D = 5°, I = -50° (after dip correction), with k = 28.7 α_{95} = 8°.

2.2.3 Results from the High Ireby Formation

Thirteen sites out of seventeen were significant prior to a.f. cleaning (Table 2.3). Within site grouping is poor ($k > 30$ only for sites 13 and 40). Two of the four non-significant sites (23 and 24) are of more acidic composition and in any case the samples were rather weathered; the other two sites (6 and 7) are in unaltered andesitic lavas. Total NRM results are grouped round D = 10°, I = -28° after dip correction. Site 13 is an exception, the *in situ* direction being close to the present geomagnetic field. The intensity ranges from 0.08×10^{-3}G to 3.0×10^{-3}G . Very similar to the distribution of intensities found in the Binsey Group.

Progressive a.f. demagnetization was applied

(Figure 2.4). For most sites, the optimum treatment was between 600 and 800 Oe. Exceptions were sites, 11, 21, 22, 40 and 41 which were adequately cleaned in 200 Oe or less. The same categories of a.f. demagnetization behaviour can be distinguished as for the Binsey Group, and in addition a common feature in the High Ireby Group is a well-marked flattening in the demagnetization curve around 600 Oe., accompanied by a sharp rise in Stability Index. With further treatment, direction, intensity and Stability Index all remain relatively constant.

After cleaning, only two of the seventeen sites (23, 24) are non-significant and these are the weathered ones (Table 2.4). All other sites (except 20) show an improvement of within-site grouping upon cleaning, although it is still poor in a few cases (6, 7, and 9). Between-site grouping improves from k = 6.7 to 25.0 upon cleaning with a mean direction of $D = 358^{\circ}$, $I = -37^{\circ}$ with $\alpha_{95} = 8^{\circ}$ (dip corrected).

2.2.4 Rock magnetics and opaque petrology

In Figure 2.5 the variation of intensity and

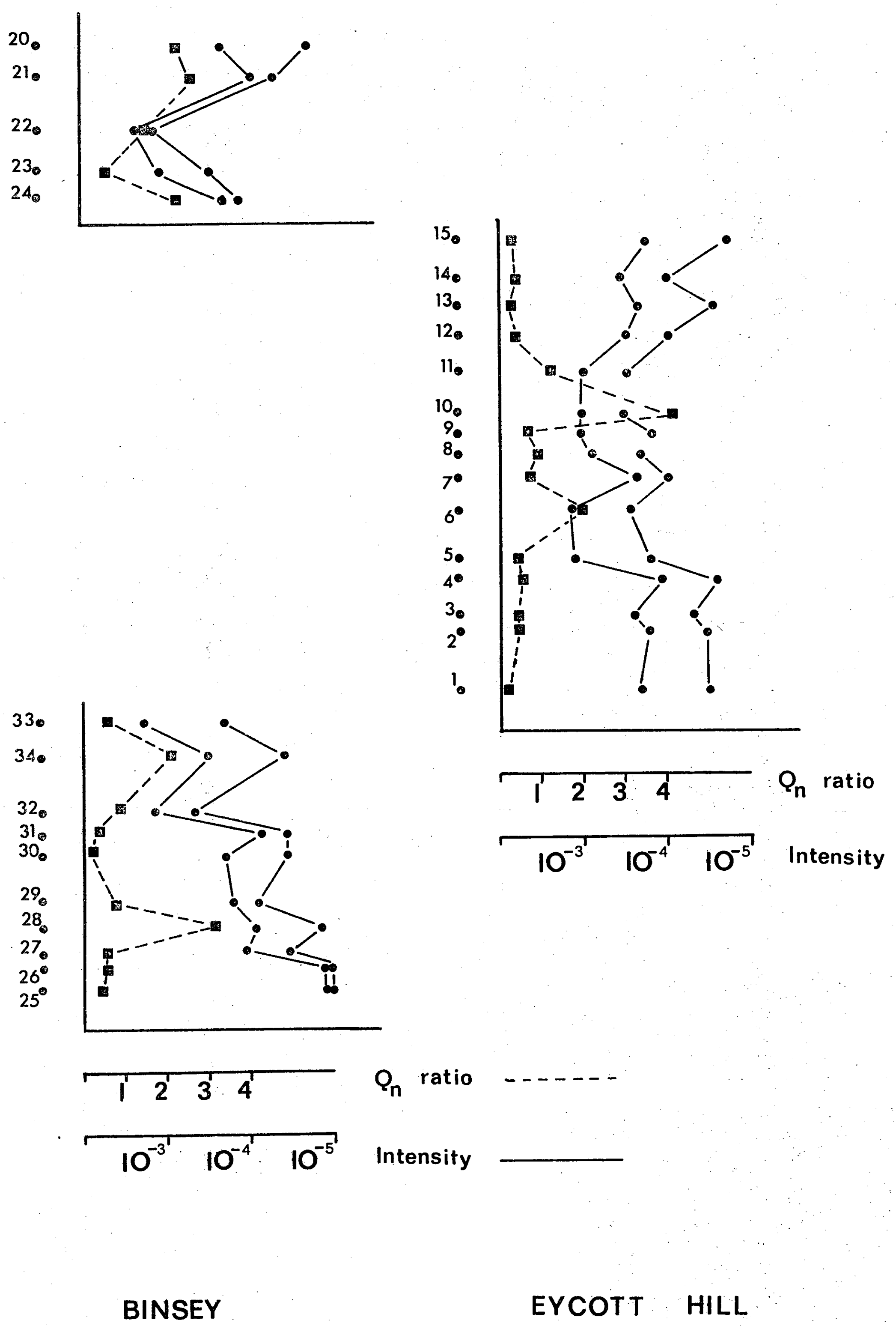


Figure 2.5. Variation of remanent intensity (NRM and a.f. cleaned) and Q_n ratio with stratigraphic level - Eycott Group.

susceptibility is plotted with respect to position in the stratigraphic succession. Intensity shows similar variations both before and after a.f. cleaning. The intensity curve is fairly uniform, but steps occur around sites 5 and 11 which were collected from pyroxene rich flow-banded andesites. Sites 20 to 24 which show the largest intensity variation exhibited over all the section, corresponds to the widest range of rock types found in any part of the succession.

Most sites have a Koenigsberger ratio (Q_n) in the range 0.1 to 1.0. IRVING (1964) has suggested that a Q_n ratio greater than 0.1 is indicative of a meaningful stable remanence. However, STACEY (1967) working on magnetic powders found that a Q_n ratio of less than 0.5 was indicative of multi-domain magnetite, and hence is inherently magnetically unstable. This criterion can only be applied to recently acquired remanence, as it does not allow for the build-up of any viscous components. A more quantitative measure of magnetic stability is provided by the changes of intensity and direction of the remanence vector during stepwise demagnetization (BRIDEN 1972, TARLING and SYMONS 1967). For this collection there is no obvious correlation between

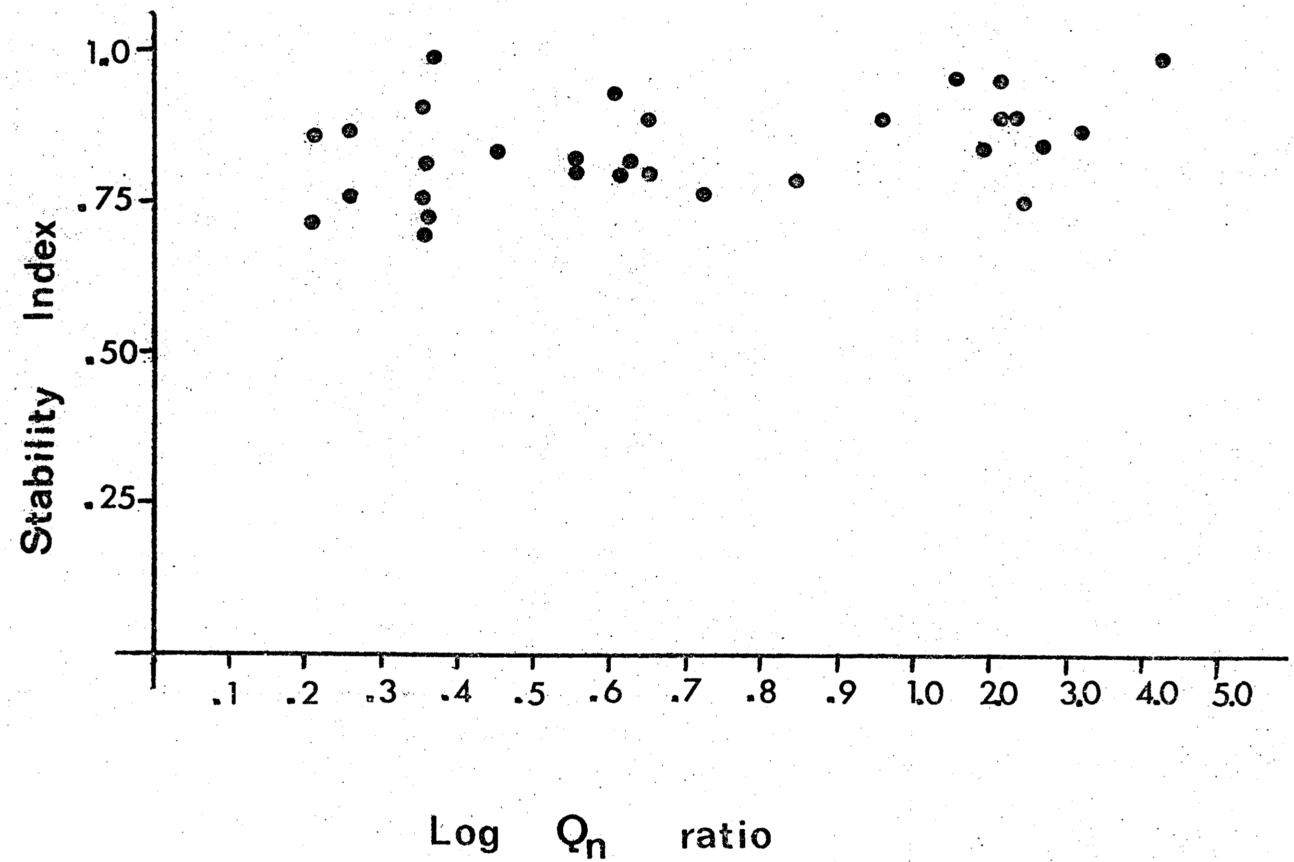


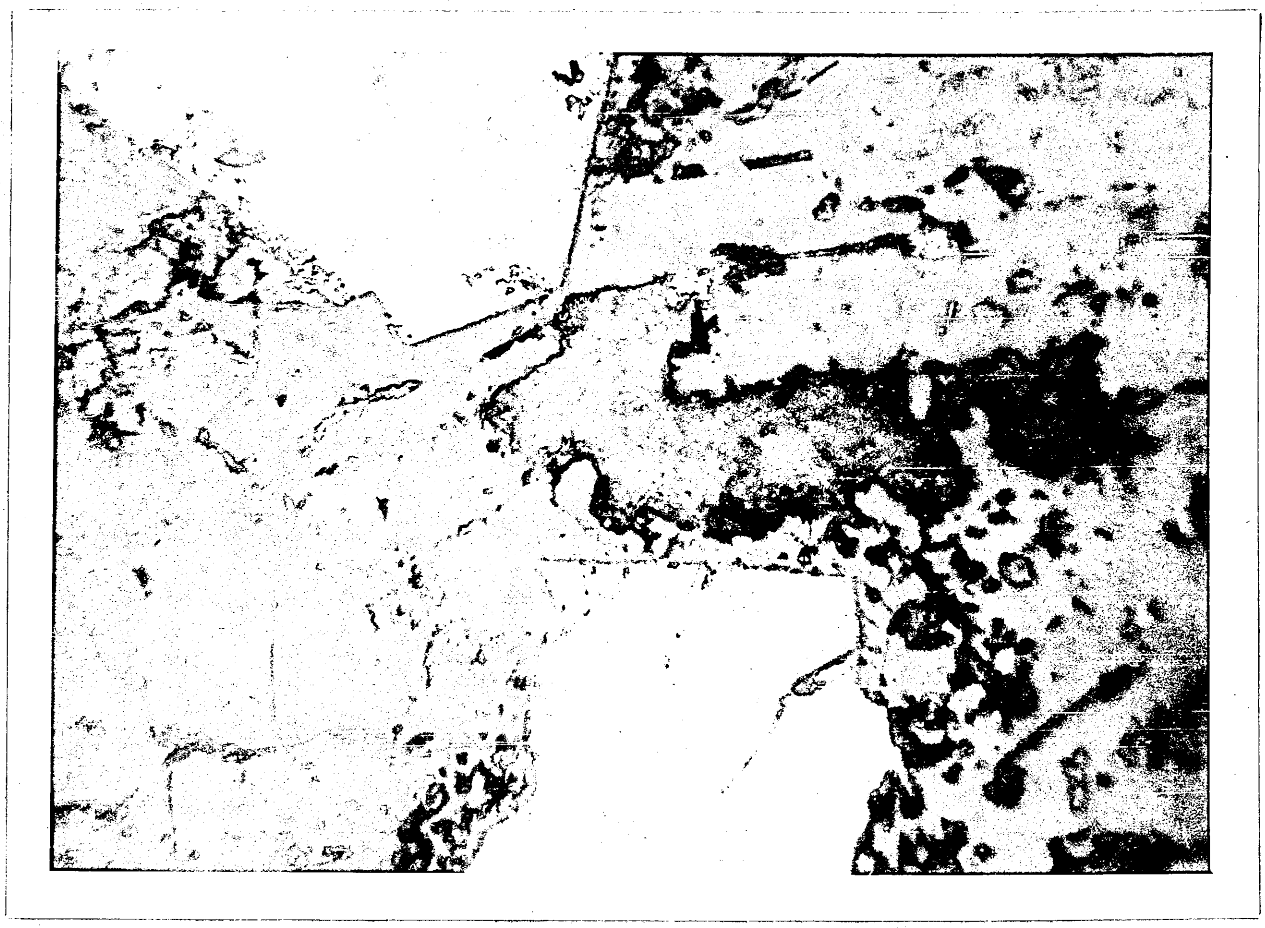
Figure 2.6. Comparison of Stability Index and Log_{10} Q_n ratio

the two stability criteria (Figure 2.6), but then, the maximum Stability Index shows little variation, and all the specimens have a Q_n ratio indicative of stable remanence.

The main constituent found in polished specimens from the lavas is fine-grained titanomagnetite (Figures 2.7 and 2.8); the more fine-grained basic rocks normally have a higher titanomagnetite content, and a Q_n ratio greater than 1.0. Although oxidation state varies between specimens from the same site, in general the oxidation class is low (M = 1/2) (WILSON and HAGGERTY 1966). Sites 21, 24 and 34 were collected from tuffaceous horizons which are interbedded with the lavas. Site 24, is highly weathered and does not carry any statistically significant remanence. The site mean directions of sites 21 and 34 are not significantly different to the overall mean. A polished specimen from site 34 showed that the rock was initially an unconsolidated tuff which has later suffered haematite metasomatism. The matrix and the grains have different oxidation states (Figure 2.9) A.f. demagnetization characteristics indicate that the remanence is carried by the secondary haematite. Similarly PIPER and BRIDEN (1973) found that soda metasomation associated with

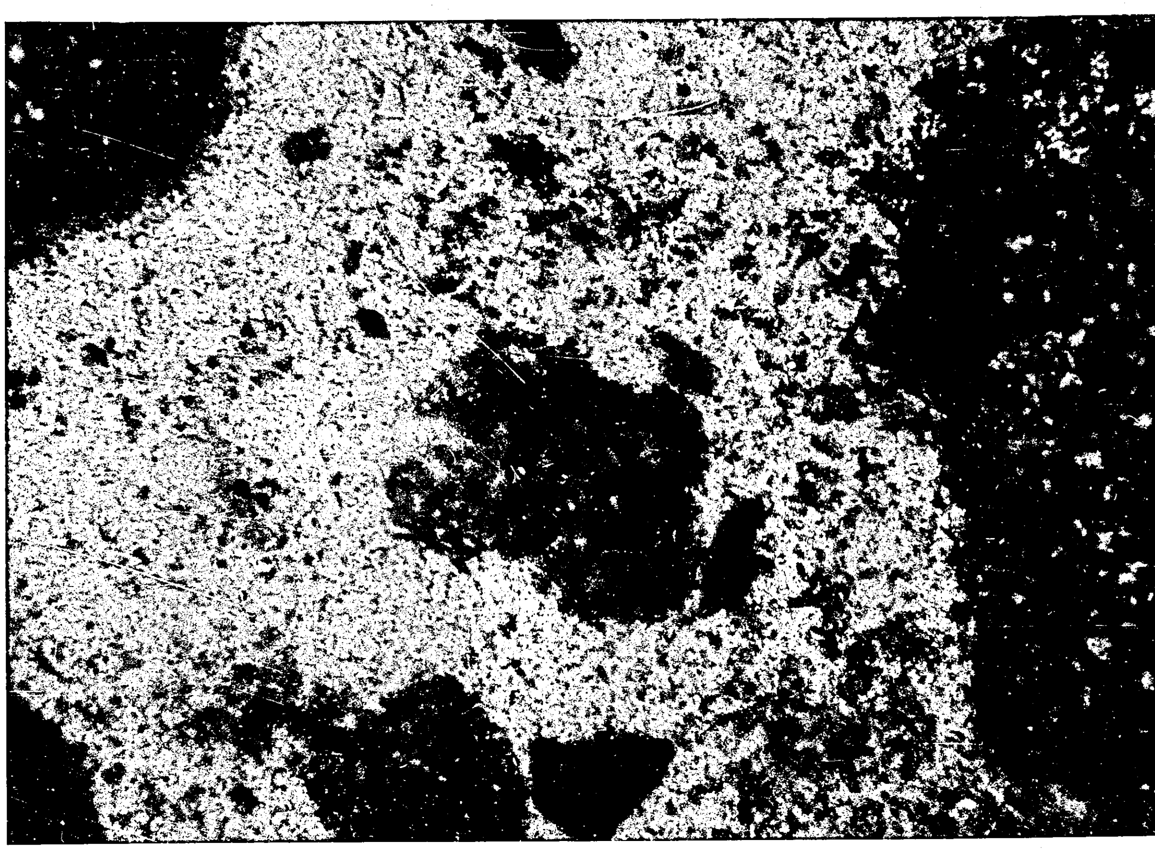
75μ

Figure 2.7. Photo - micrograph of Eycott - type lava, the titanomagnetite is intergrown with the plagioclase laths.



20μ

Figure 2.8. Detail of titanomagnetites from the Eycott Group.
All grains showing some low temperature alteration - granulation.



150μ

Figure 2.9. Crossed nicols photomicrocraph of a sample from site 34, showing the individual grains of the tuff. The remanence is carried by sub-microscopic hematite.

intrusion, produced a 'secondary' remanence which is completely in agreement with the syngenetic remanence.

2.2.5 Interpretation

Between the two sections on Binsey and Eycott Hill there is a large difference in dip and strike. The results in Table 2.5 are based on a single tilt correction by rotation about the present strike. Combining all the results, simple tilt correction gives a fold test significant at the 99% level (McELHINNY 1964). There have been several suggestions that the underlying Skiddaw Slates have been subjected to more than one folding episode (SIMPSON 1967, 1968, HELM and ROBERTS 1971, and WADGE 1971). WADGE (1971 contends that the Skiddaw Slates are folded by a major anticline which plunges shallowly to the ENE while HELM and ROBERTS (1971) argue in favour of a steeper plunge towards 340°. These hypotheses envisage folding of the Skiddaw Slates prior to the onset of Borrowdale Group volcanicity. Since it has been shown that the Eycott Group pre-dates the Borrowdale Volcanic Group (NUTT 1968, WADGE 1972), and that the Skiddaw Slate-Eycott Group junction is conformable (DOWNIE and SOPER 1972, EASTWOOD *et al.* 1968), it is worth testing the applicability of these hypotheses to the 'northern' volcanics themselves.

Combining the results from each Formation, a tilt-corrected mean remanence direction was calculated for each section. Using the test of WATSON (1956 a) it can be shown that these directions are significantly different at the 99% level. To test whether this discrepancy is a result of more complex deformation the effects of all possible two stage concentric folding were investigated. Each element of folding was allowed for in turn, starting with the younger. Accordingly Figure 2.10 shows the results of first removing a plunge, and then allowing for the residual dip at each of the two sections. From this analysis, the optimum plunge is taken as giving minimum angular discrepancy (Δ) between the results from the two sections. In Figure 2.10 the optimum plunge which might be inferred from the palaeomagnetic data is indicated by the stippled area, the plunge suggested by HELM and ROBERTS (1971) falls in this zone, though the plunge advocated by WADGE does not. However, the Fisherian precision corresponding to this optimum hypothesis is 25.78 compared with 21.37 if zero plunge is assumed, and 19.50 on WADGE'S hypothesis. These differences in precision are not significant with any high degree of probability, and the analysis merely suggests that

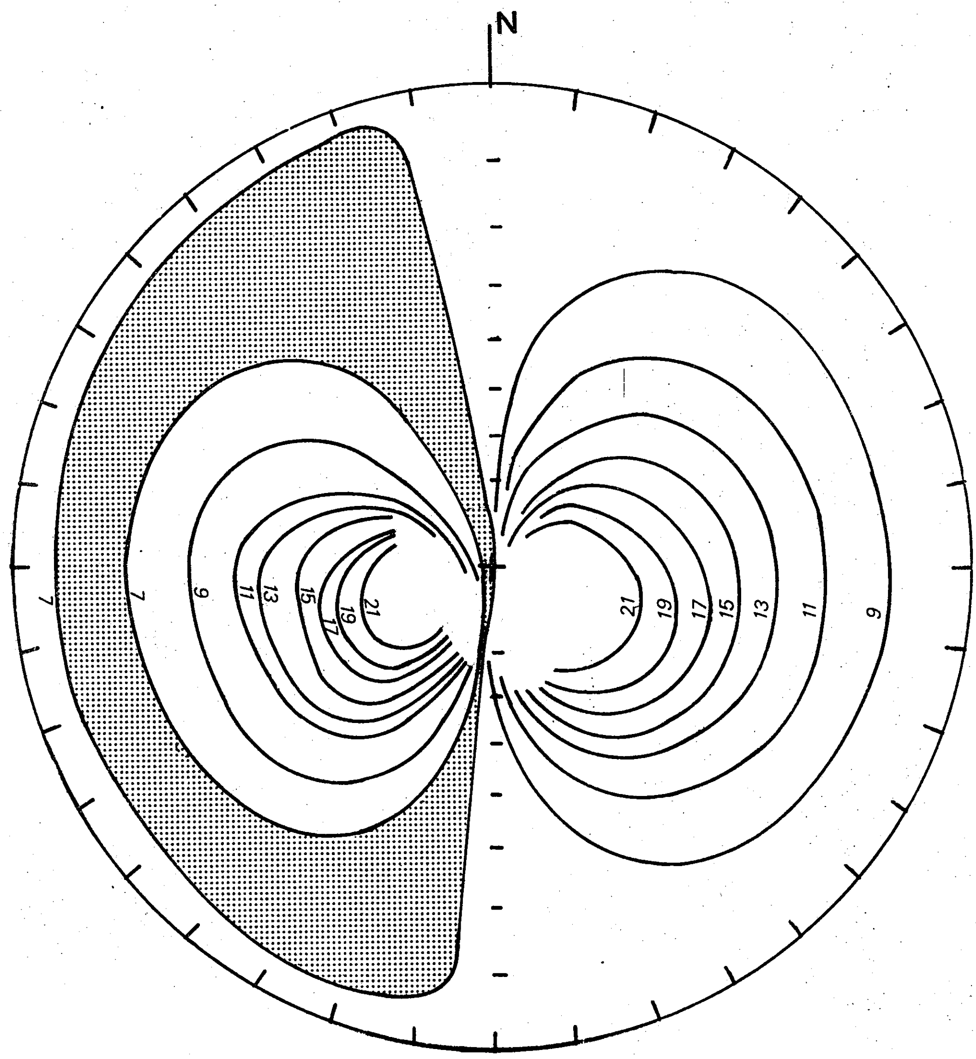


Figure 2.10. Angular separation (Δ) between the remanence directions from the two limbs of a plunging fold plotted as a function of applied plunge correction. The stippled area indicates the optimum plunge inferred from the palaeomagnetic data. Equal area stereographic projection.

WADGE'S contention is less likely to be valid than the alternative hypothesis. RAMSAY (1961) has shown in the general context of structural geology that failure to recognise plunges of 30^{o} or less leads only to 'small' errors in directional estimation, ('small', that is, by comparison with the confidence limits commonly associated with palaeomagnetic results). Hence for palaeomagnetic purposes it is adequate to treat the deformation as a rotation (or rotations) about the present local strike at each locality. The simplest interpretation would be of a single rotation about that strike although progressive tightening of this essentially simple structure is equally compatible with the evidence.

In Table 2.5 tilt corrected mean remanence directions are given for both the High Ireby Formation and the Binsey Formation. In each Formation simple tilt correction produced a marked increase of precision, constituting a fold test of remanence significant at the 95% level (McELHINNY 1964).

An F-test (WATSON 1956 a) shows that the mean stable remanence directions of the two Formations are significantly different. This could have arisen from a number of causes. First, an episode of folding occurring between the two Formations might be involved. A test of the kind exhibited in

Figure 2.10 is not strictly applicable because of the irregular distribution of the data available. Moreover there is no geological evidence for its reality, indeed the dip and strike is remarkably uniform throughout each of the sections. Second, the significance of the difference might be a product of the statistical analysis. The WATSON and IRVING (1957) analysis of dispersion, in the High Ireby Formation in particular, shows that dispersion arises mainly from within-site variation, and hence the circle of confidence about the between-site mean is very small, inferring that the difference between the two Formations is likely to be real. Third, even if real, the difference ought either to be due to genuine polar shift or failure to average secular variation. In Chapter 5 it will be pointed out that although there is no evidence for systematic polar shift within the Ordovician of the British Isles, that this may simply be due to inexact tilt correction. On the other hand the possibility that secular variation has not been adequately averaged cannot be eliminated, because in the absence of intercalated sediments there is no indication of the time-span covered by the lava Formations. Hence, a best estimate of the local Ordovician geomagnetic field is given by combining the data for the whole of the Eycott Group., (Table 2.5). The overall mean direction of the 29 significant sites is $D = 0^{\circ}$, $I = -43^{\circ}$ ($\alpha 95 = 6^{\circ}$), which yields a palaeomagnetic pole at Lat = 10°S, Long = 176°E ($d\psi = 5^{\circ}$, $d\chi = 7^{\circ}$).

All samples from both sections have the same polarity. Both the Builth Volcanic Series (PIPER and BRIDEN 1973) and the Aberdeenshire Gabbros (SALLOMY and PIPER 1973) have the opposite polarity and yet are dated at approximately the same age. The contruction of a polarity - time scale may help to define their relative ages more precisely.

Even after a.f. cleaning some sites (5, 23, 24) were rejected from the final analysis because they gave random results. These sites all lie close to the boundary between the Binsey and the High Ireby Formations, and therefore may possibly have been formed at an 'instant' when the geomagnetic field was much weaker. Although site 24 shows signs of incipient weathering and is more acidic in composition, it is nevertheless petrographically and magnetically very similar to site 21 which has a well defined remanence, sites 5 and 23 are more basic fine-grained rocks, showing no signs of weathering.

The rocks are not petrographically distinct having the same quantity and composition of magnetic mineral phases as the other rocks in the sections. Nor are they magnetically distinct in terms of their remanent intensity or susceptibility. Hence the explanation of this possibly 'randomly magnetized horizon' remains uncertain.

Site 25 is from the lowest lava in the Binsey Formation, it was collected in a small quarry at Whitefield Cottage. The lava is overlain by mudstones which pass upwards into subaerially deposited lavas - the 'Passage Beds' (EASTWOOD et al 1968). Site 25 is separated from the main Binsey traverse by a N-S trending fault. The dip in the quarry is only 30° compared with the 70° dip of the main section. Simple tilt correction of 30° brings the remanence into line with that of all the sites in the Eycott Group. From this palaeomagnetic evidence it is suggested that there is neither a substantial time interval nor an appreciable tectonic event between the formation of the lavas at site 25 and the next oldest sites (site 26 etc.). This supports geological evidence for stratigraphic continuity in the 'Passage Beds' in this quarry, which is inferred from the absence of any discernable disconformity and from micropaleontological continuity (DOWNIE and SOPER 1972). Furthermore, sediment deposition was continuous at Eycott Hill throughout the time in question.

2.3 The Borrowdale Volcanic Group

2.3.1. Geology and sampling

A thick pile of lavas and volcano-clastics which outcrop as a broad band across the southern part of the Lake District is referred to as the Borrowdale Volcanic Group. The base of this sequence has a problematical relationship to the underlying Skiddaw Slates (SOPER 1970, HELM and ROBERTS 1971). The best interpretation is that the contact can be locally conformable, unconformable, or thrust (MOSELEY 1972). The top of the volcanic succession is now marked by the unconformably overlying Coniston Limestone Group. Estimates of the time-span of eruption are bounded to the period Llanvirn-Caradoc. The younger limit is slightly misleading, as time must be allowed for the folding of the volcanics prior to the deposition of the Coniston Limestone Group, whose present outcrop transgresses a thickness of some 2500 m. of volcanics.

Within the lava pile there are no sediments, which together with an almost complete lack of fossil material, and the impersistence of individual volcanic horizons makes stratigraphic correlation difficult. Estimates of total thickness are dependant upon measuring long traverses which obviously introduces many problems. Total thickness is variable; MITCHELL (1956) proposed a maximum of 4000m., but FIRMAN (1957) working near Wastwater has argued that 5000m. is a more likely estimate. The lavas and volcanoclastics mostly show a westerly provenance but some of the lower horizons around Wastwater are indicative of a north-easterly source.

Mapping of detailed areas involving the erection of local stratigraphic sequences has produced a number of correlation schemes between adjacent areas. MITCHELL (1956) gave a general review of the regional stratigraphy. More recent mapping by MOSELEY (1960, 1964), OLIVER (1961), and NUTT (1968) has verified most of MITCHELL'S early correlations, although any correlation with the Eycott Group has since shown to be completely erroneous.

Rock types in the Borrowdale Volcanic Group vary from fine-grained tuffs to agglomerates, interbedded with numerous flows of andesitic and rhyolitic lava.

A concise summary of the structural evolution of the Lake District has been given by Moseley (1972). The Volcanics have been folded into a series of simple open synclines and anticlines, mostly with an ENE axial trend. Difference in structural style between the volcanics and the underlying sediments, has been interpreted by many (SIMPSON 1967, 1968, HELM 1970) to imply a pre-Borrowdale orogeny, but as pointed out by MOSELEY (1972) large competence differences can equally lead to major variations of fold style. Likewise the presence of a penetrative cleavage of end-Silurian age has been interpreted as indicative of a climactic orogeny at that time (SOPER and ROBERTS 1971).

The material reported in this study was collected from three localities all in the eastern part of the Borrowdale Volcanic outcrop, Haweswater (HANCOX 1934, NUTT 1968), N.W. Ullswater (MOSELEY 1964), and Kentmere (MITCHELL 1929). In the Haweswater area NUTT (1968) recognised two distinct stratigraphic successions separated by a N.E. trending fault. To the south-east the succession is similar to that near Kentmere (MITCHELL 1929), while to the north-west it correlates to the succession found by MOSELEY (1960, 1964) around Ullswater.

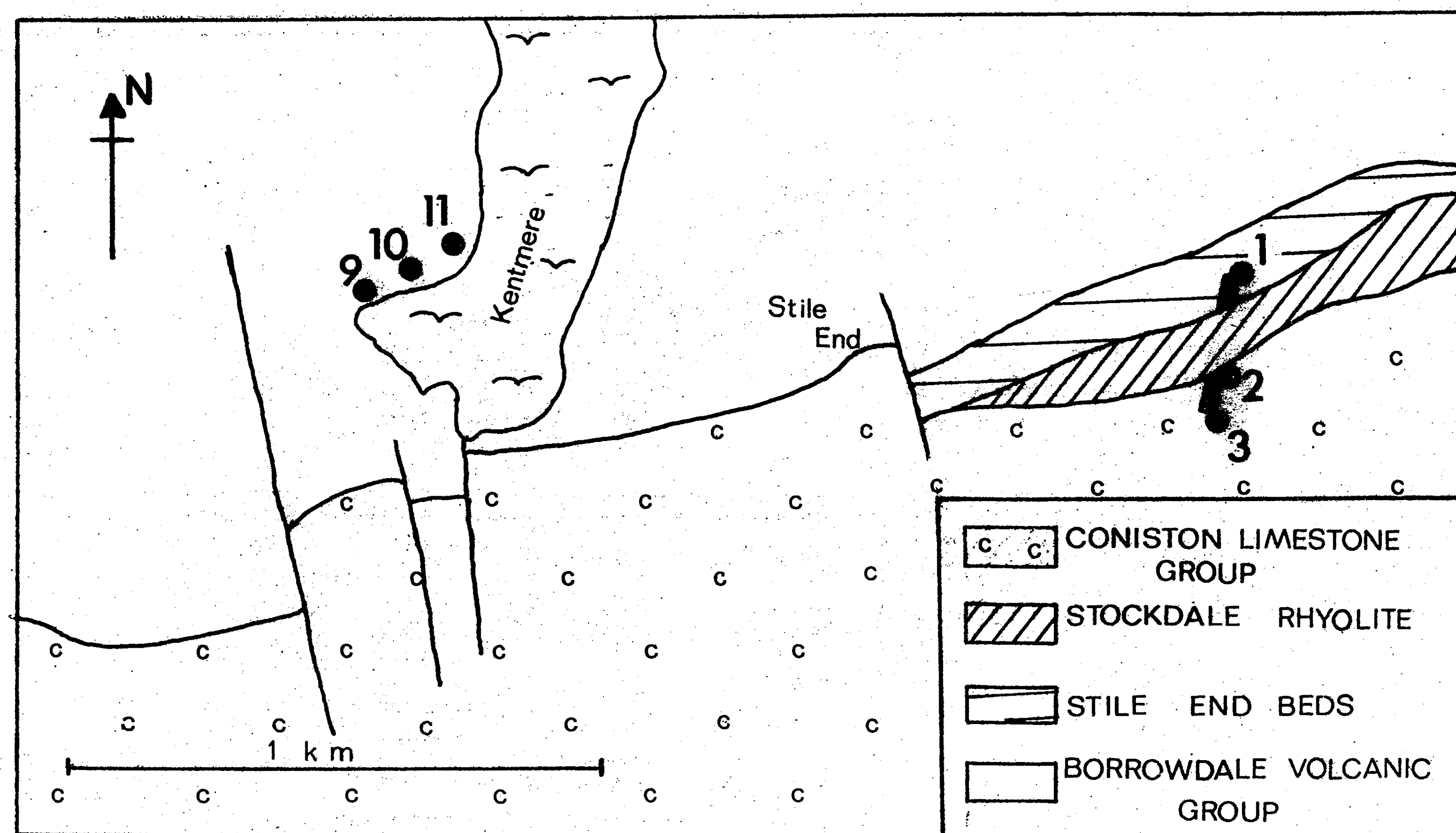


Figure 2.11. Geology and sampling localities - Kentmere.

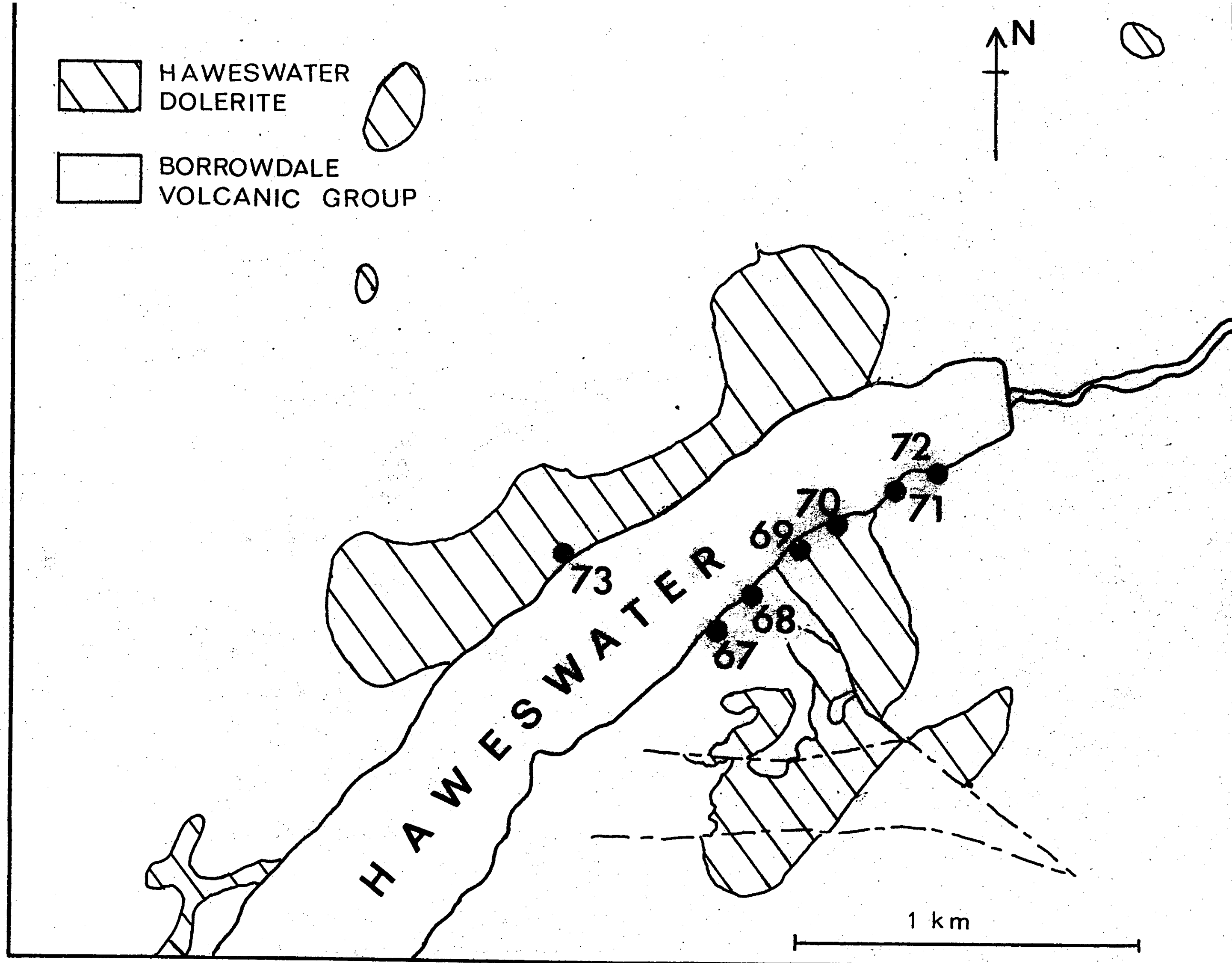


Figure 2.12. Geology and sampling localities - Haweswater.

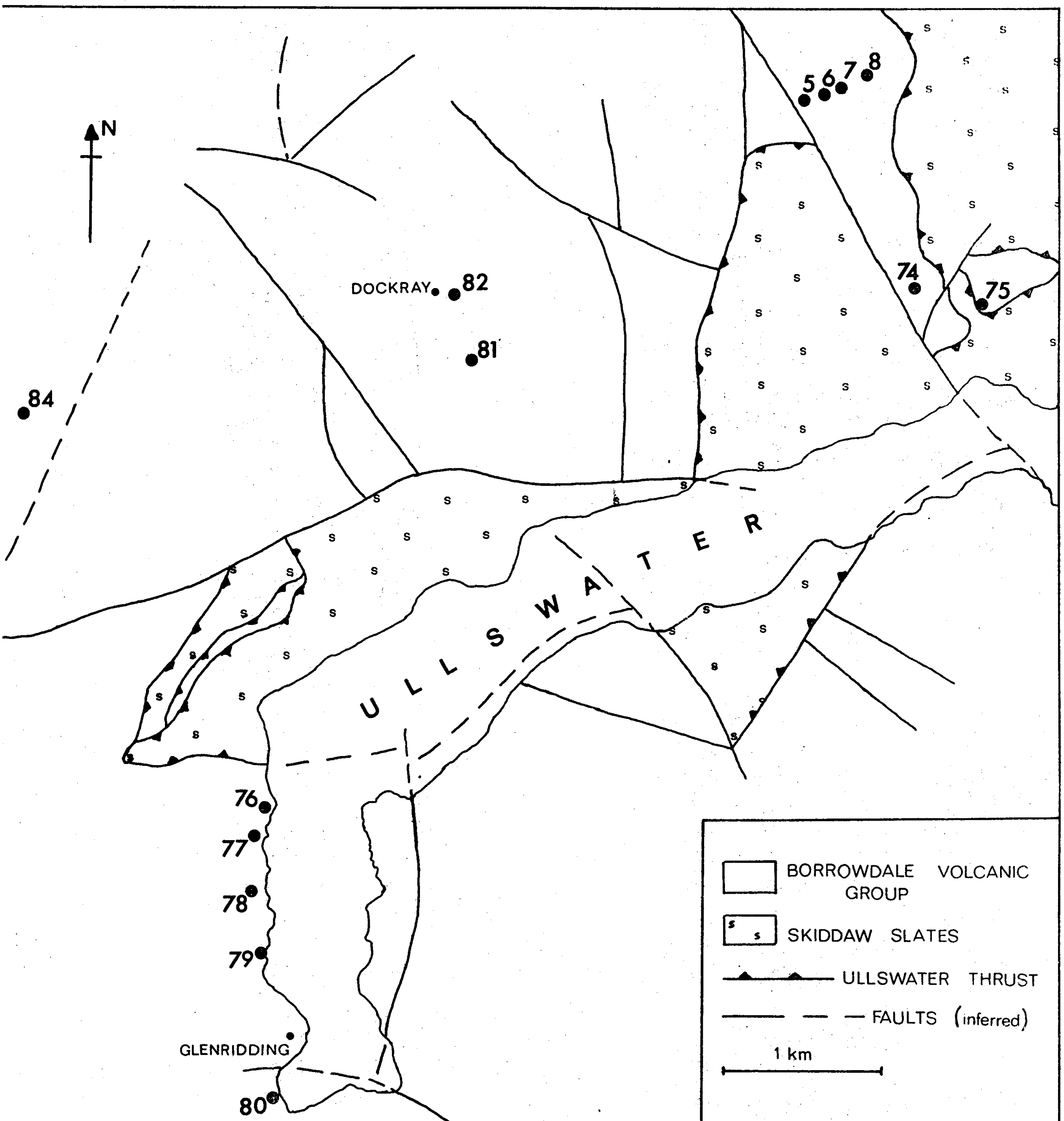


Figure 2.13. Geology and sampling localities - Ullswater.

The fault plane also cuts an intrusion of Ordovician age; the Haweswater Dolerite, which NUTT (1968) has interpreted as a vent related to the Borrowdale Volcanic Group.

Twenty-five sites were collected from the Borrowdale Volcanic Group and associated intrusives. In the Haweswater area samples were taken from the Intrusive Complex, its metamorphic aureole, and also from apparently unaltered Borrowdales. In Kentmere three sites were also sampled in a N.E. trending dyke which outcrops near Stile End. The dyke intrudes the base of the Stockdale Rhyolite (part of the local Coniston Limestone Group), implying a post-Caradocian age. Sampling locations and the generalised local geology are shown in Figures 2.11 - 2.13.

2.3.2. Results

Standard laboratory techniques were applied to the collection. Three of thetwenty-five sites have statistically random site mean directions (Table 2.6). Sites 67 and 68 have very low site mean intensities ($<0.6 \times 10^{-6}$ Gauss), undoubtedly related to alteration in the metamorphic aureole of the Haweswater Dolerite.

Samples from site 74 are highly reddened and granular, and probably of tuffaceous origin, hence, remanence is not strictly syngenetic. The significant site means can be separated into two groups: (a) principal group centred on D = 340°, I =-33°, (dip corrected), and (b) anomalous group with steep inclinations (both positive and negative), and declinations which do not fall in the range 330° to 030°.

Progressive a.f. demagnetization produced similar decay curves for most sites. Characteristics of these samples are little (or no) direction change, regular intensity decay, after an initial (up to 200 Oe.) rapid direction change. For sites 67 and 68 the demagnetization curves are erratic and it was not possible to select an optimum field for cleaning. As initially the samples were weakly magnetized, this erratic behaviour, may be an inherent magnetic property, or, may have resulted from the measuring technique. Possible sources of weak fields present during a.f. treatment are RRM or ARM (WILSON and LOMAX 1972) or static build up on the pick-up shields of the spinner magnetometer which at intensities of $<0.6 \times 10^{-6}$ Gauss is occasionally noticeab

After a.f. treatment five sites have statistically random remanence (Table 2.7). The site mean directions again fall into two groups. A 'principal' group based on twelve sites (Table 2.8) with a mean of $D = 338^{\circ}$, $I = -46^{\circ}$ $k = 20$ (dip corrected), which corresponds to a virtual geomagnetic pole at Lat = 6°N, Long = 196°E ($d\psi = 8^{\circ}$, $d\chi = 13^{\circ}$). The second group (Table 2.8) gives an 'anomalous' mean direction $D = 337^{\circ}$, $I = +80^{\circ}$, $k = 12$, $N = 8$ sites, (in situ), which corresponds to a pole at Lat = 71°N, Long = 334°E ($d\psi = 30^{\circ}$, $d\chi = 32^{\circ}$).

Simple tilt correction of the 'principal' group increases the overall precision by five times a fold test significant at the 99% level (McELHINNY 1964, COX 1969). All sites have the same polarity, as all other studies from the Ordovician of the Lake District. The overall precision parameter ($k = 20$) is lower than in similar volcanic sequences of comparable age (Eycott Group and the Builth Volcanic Series). A Watson-Irving (1957) two tier analysis shows that between-site precision is greater than within-site precision ($k_B = 27.9$, $k_W = 19.8$). However this analysis is only strictly applicable where the individual site mean precisions are fairly constant.

In this collection k ranges from 6 at site 78 to 145 at site 10. Even so, the overall precision (^{k}HAT = 270) calculated from the two tier analysis is high, which indicates that the low value of k is mainly produced because of within-site dispersion. A multiple-tilt test (BRIDEN and MORRIS 1973) on these results merely emphasised that simple tilt correction produced minimum angular separation (Δ) of the mean remanence direction from each limb of the major ENE-WSW trending anticline. Although the Skiddaw Slates exhibit complex folding styles, there is no evidence for anything but simple folding of the Volcanics.

The mean remanence directions of the Eycott Group and the Borrowdale Volcanic Group are significantly different(WATSON 1956 a). There are a number of possible reasons. Firstly, the difference could be purely statistically. Secondly, the Borrowdale Volcanics lie stratigraphically above the Eycott Group DOWNIE and SOPER 1972, WADGE 1972), so the difference may be due to polar shift. Thirdly, if the lavas were erupted over a short period of time it is possible that secular variation effects have not been eliminated. The difference in mean direction between the two groups is solely in dedination (Eycott Group D = 0^{o}, 1 = -45^{o}, Borrowdale Group D = 338^{o}, 1 = -44^{o}). In the Borrowdale

Volcanic Group only sites 4 and 10 are from Kentmere where the relationship between the Borrowdales and the Skiddaw Slates is unknown. MOSELEY (1960, 1964) has shown that the contact in the Ullswater area is a steeply inclined thrust, it is possible that rotation of 20^{o} could have resulted from movement on the thrust. With the present data it is not possible to decide which interpretation is correct.

The 'anomalous' group's mean direction cannot be interpreted in terms of Palaeozoic palaeomagnetism. The analysis of this direction is deferred to Section 5.5 where other anomalous results are also considered.

2.3.3 Diorite dyke-Stile End

Total NRM of all three sites collected from the dyke at Stile End are significantly grouped, (Table 2.9). The site means are loosely grouped around $D = 137^{o}$, $1 = +68^{o}$, $k = 3.7$ (in situ).

After a.f. cleaning only two of the three sites have significantly grouped remanence (Table 2.9). The *in situ* mean (Table 2.10) of these two results cannot be interpreted in terms of any locally inferred Palaeozoic (or younger) geomagnetic field direction. Tilt correction for the overlying Coniston Limestone Group gives a mean direction of D = 5°, I = -53°, k = 6, based on twelve samples. Geologically the dyke must be post-Caradocian and pre- end-Silurian tilting and by reference to other palaeomagnetic studies in Britain (BRIDEN, MORRIS, and PIPER 1973) pre- Upper Llandovery. Because of the small sample numbers, it is not statistically valid to compare this mean direction with other Lake District results, but clearly it agrees more closely with the Eycott Group rather than the Borrowdale Group result. Further studies in progress should clarify whether the apparent polar shift between the two volcanic groups, is real, statistical or tectonic.

2.4 Carrock Fell Complex

2.4.1. Geology and sampling

The Carrock Fell Complex is intruded along the complicated junction between the Eycott Group and the Skiddaw Slates (Figure 2.2). Initially WARD (1876) interpreted the Complex as metamorphosed volcanics. HARKER (1894, 1895) remapped the area and recognised it as a major intrusion of gabbro, diabase and granophyre.

Subsequent mapping by the (then) Geological Survey (EASTWOOD *et al.* 1968) confirmed this interpretation and introduced finer subdivisions.

The rock types are arranged in a series of steeply inclined sheets, running E-W parallel to the long axis of the Complex (Figure 2.14). HARKER (1894) noting the compositional variations and distribution of rock types, suggested that the mass represented a single magma injection differentiated *in situ*. EASTWOOD *et al.* (1968) state that the 'several distinct types maintain their identities over considerable (lateral) distances and have fairly rapid transitional contacts'. This suggests deep-seated differentiation with pulses of magma intruded as dyke sheets. Dykes of similar composition and trend to the Gabbro Complex can be found in the surrounding country rock. The oldest intrusions within the Complex are the gabbros, beginning with a uniform melagabbro, and concluding with a leucogabbro. These were followed by the diabase, and finally the granophyre which occupies a central position within the Complex, marks the last phase of intrusion.

The age of intrusion is uncertain. The

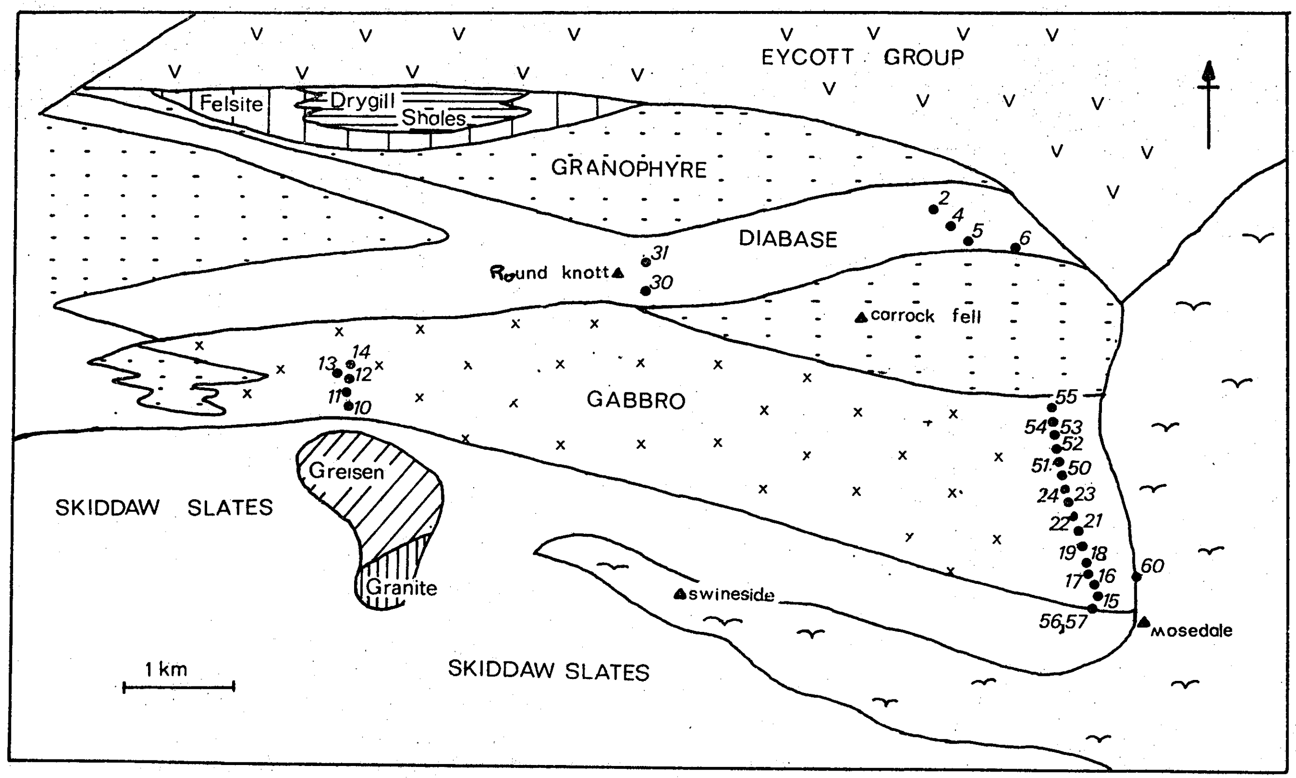


Figure 2.14. Geological sketch map and sampling localities - Carrock Fell.

only radiometric date (BROWN et al. 1964) is on the hornfels, from the metamorphic aureole of the Complex above Mosedale village, this gives an age younger than the Skiddaw Granite, which itself has a metamorphic aureole in the Gabbro.

Exposure is best along the eastern margin of the Complex where cliffs up to 30m. exist. Thirty sites were collected by field drill (Figure 2.14); sites were taken from the northern (2, 4, 5, 6) and southern margins, the Round Knott diabase (30, 31, 32) and from the metamorphic aureole of the Skiddaw Granite (10, 11, 12, 13, 14).

2.4.2. Results

Of the total NRM results only 18 of the 30 sites were significant ($p = 0.05$, Table 2.11). Individual directions show a planar distribution near the N - S vertical plane which may indicate varying proportions of ancient remanence together with a secondary component near the present geomagnetic field; no realistic NRM mean direction can be quoted. The exceptional range of tota NRM intensities (0.3×10^{-3} G to 7.0×10^{-6} G) presumably reflects the wide variety of rock types, and perhaps locally, the incidence of metasomatism.

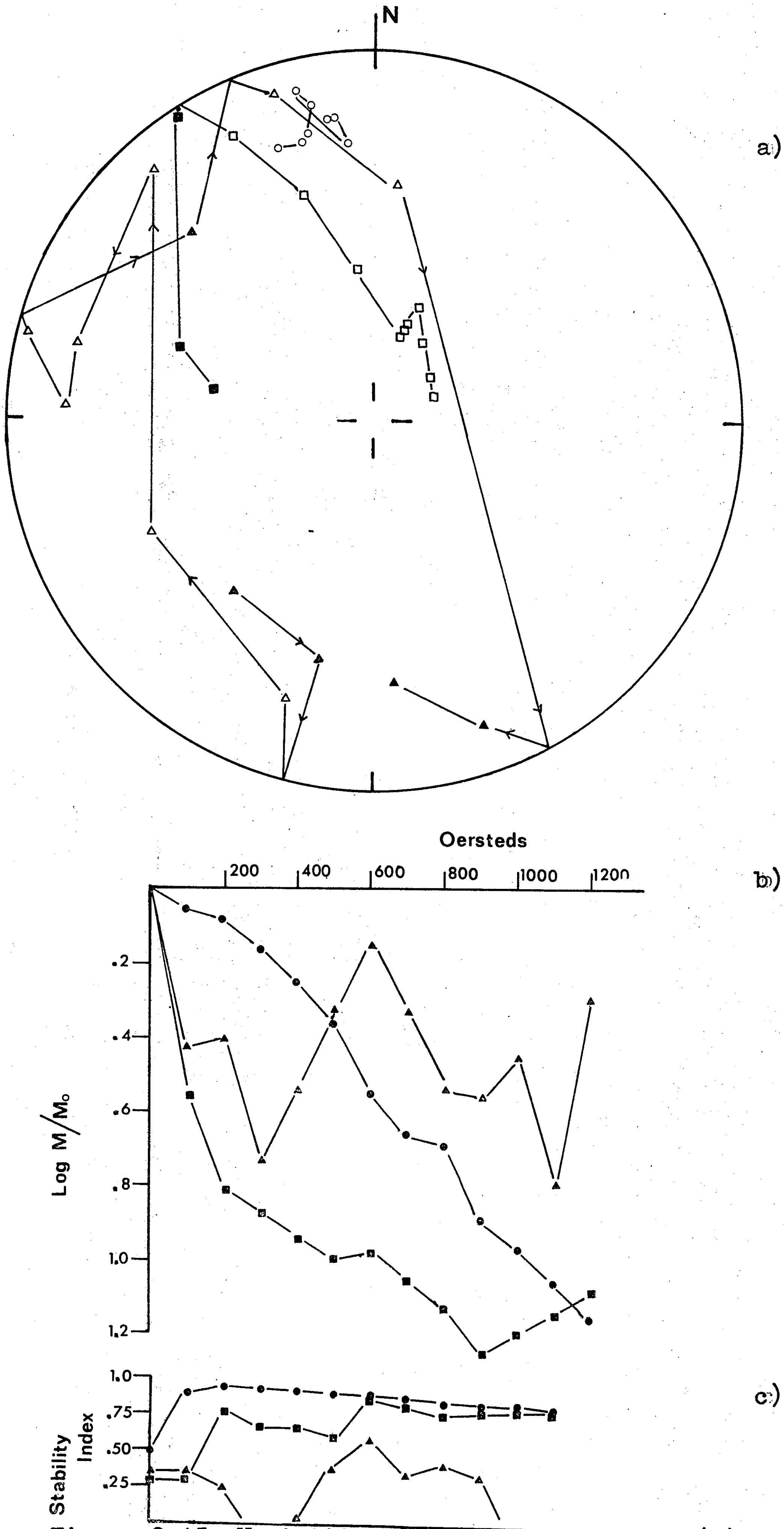


Figure 2.15. Variation of remanence direction(a),intensity (b), and Stability Index (c) upon a.f. demagnetization.

Three groups of progressive demagnetization curves can be recognised:

(1) Sites 6, 10, 11, 12, 13, 14, 31, 32, 57, and 60. Direction and intensity change randomly and Stability Index is erratic during demagnetization. It is impossible to select an optimum field for cleaning. Sites 10, 11, 12, 13 and 14 are from the metamorphic aureole of the Skiddaw Granite. Metasomatism, associated with granite intrusion, extensively chloritized and albitized the gabbro; ilmenite and magnetite was altered to leucoxene and sphene. Sites 31 and 32 from the Round Knott diabase also show this complex behaviour, possibly due to IRM as these sites were collected from near the peak of Carrock Fell. No useful palaeomagnetic results can be deduced from sites within this group.

(2) Sites 2, 4, 15, 16, 17, 18, 19 and 30. Although these sites have smoother curves than group 1, they are still not simple. The Stability Index curve of this group is dintinctly stepped (Figure 2.15) - steps at 200 Oe and 800 Oe. being most common. Intervals of little intensity and direction change are common. It is possible to select an optimum field for cleaning.

(3) The remaining sites exhibit a uniform Stability Index, intensity decays exponentially, and the direction remains fairly constant throughout treatment (Figure 2.15).

After a.f. cleaning seventeen sites have significantly grouped remanence (Table 2.12). None of the sites from the metamorphic aureole of the Skiddaw Granite have any systematic remanence. The contact between the Complex and the Skiddaw Slates is exposed on the crags above Mosedale village. Site 56 is from the gabbro and site 57 is from the adjacent baked contact. While site 56 (gabbro) gives a mean direction not significantly different to the other sites, site 57 (baked contact) has non-significantly grouped remanence. A contact test is therefore inconclusive. Site 60 is from a large xenolith of the Eycott Group in which it was possible to measure original igneous flow-banding. Assuming, no rotation or remagnetization of the lava resulting from Gabbro Intrusion then a tilt corrected result should give a direction similar to that in the Eycott Group. The NRM directions are distributed along a N-S meridian, even after a.f. cleaning the sample directions remain randomly distributed. Only those samples with the greatest magnetic moment yield tilt corrected directions, which are comparable to the locally inferred geomagnetic field. This may be fortuitous and therefore this test does not provide any more information on the mode of intrusion of the Gabbro.

Susceptibility (χ), remanent intensity (Jo), and Stability Index (S.1.) exhibit similar variations across the Complex (Figure 2.16). For most sites Q_n lies between 0.1 and 1.0. All four curves show a significant break at sites 19 and 52, outside these two sites the parameters are generally more irregular and lower than the values between them. Figure 2.17 shows the variation of remanence direction across the southern margin of the Fell, again significant direction changes occur at sites 19 and 52. Both these sites are from leucogabbros, having little opaque ore content, which is mainly in large unexsolved grains of ilmenite. Site 54, apart from site 19, the only other non-significant site from the southern margin of the complex, is a gabbro-pegmatite having homogeneous ilmenite crystals up to 1.25 mm. in length. Polished specimens of the remaining sites all contain subsidiary pyrite and chalcopyrite. The 'magnetites' occur in two phases, large homogeneous xenomorphic ilmenite grains, and elongate fine titano-magnetites, which occur as exsolution

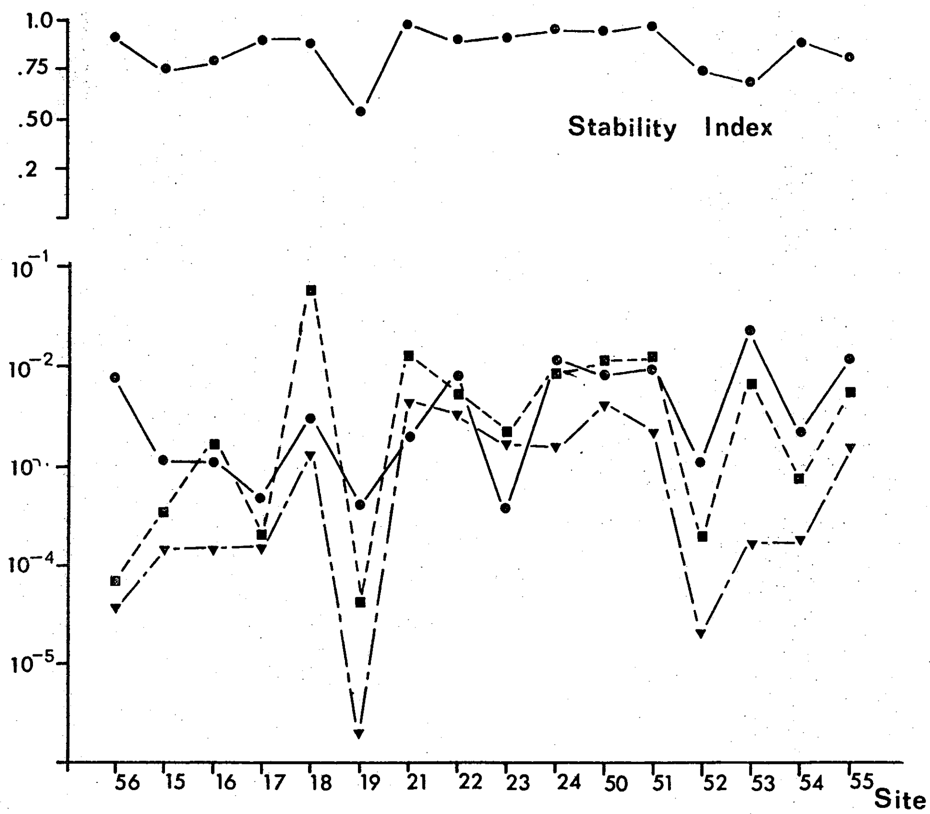


Figure 2.16. The variation of Stability Index, remanent intensity (NRM(■) and a.f. cleaned(▼)), and susceptibility (•) across the southern margin of Carrock Fell.

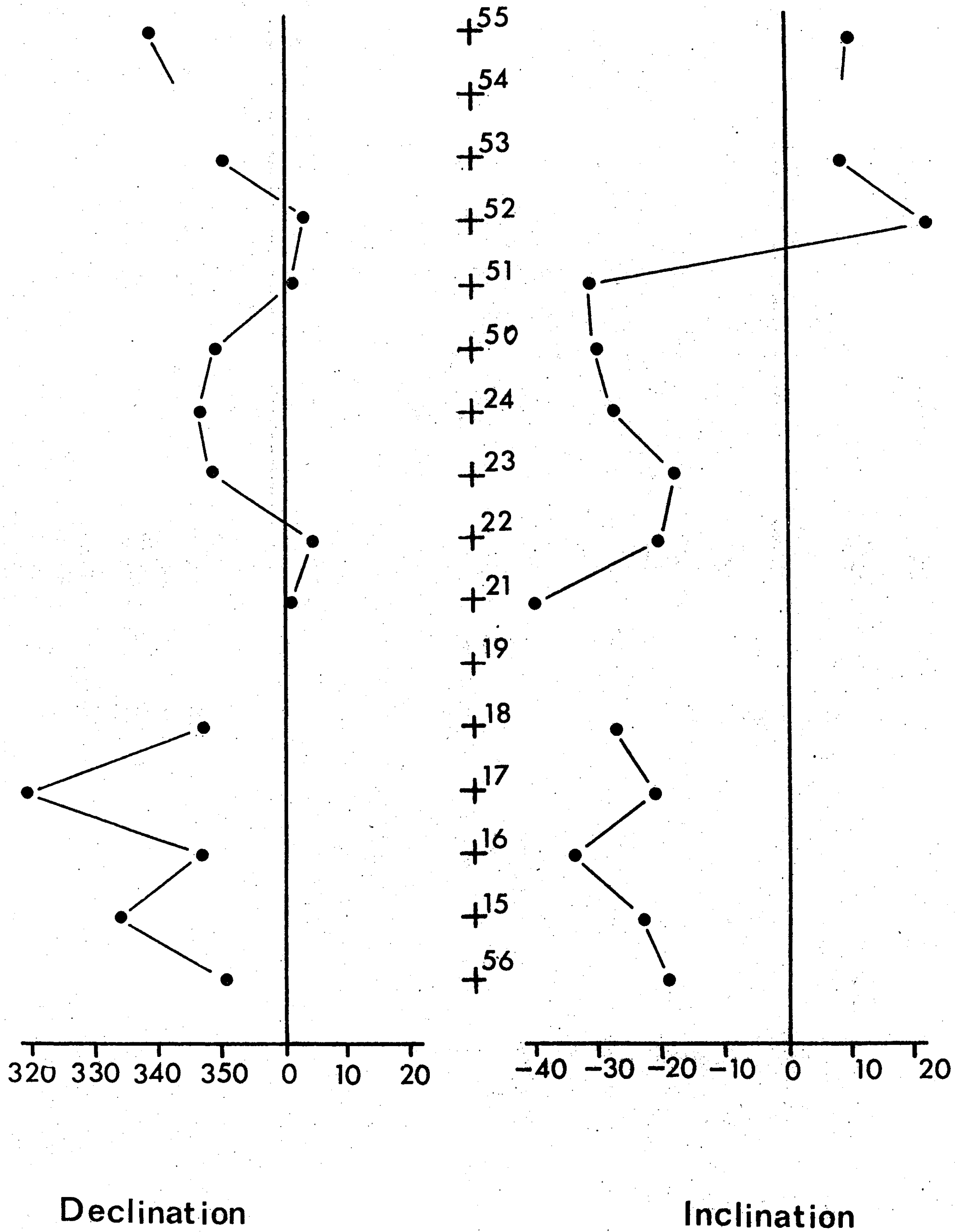
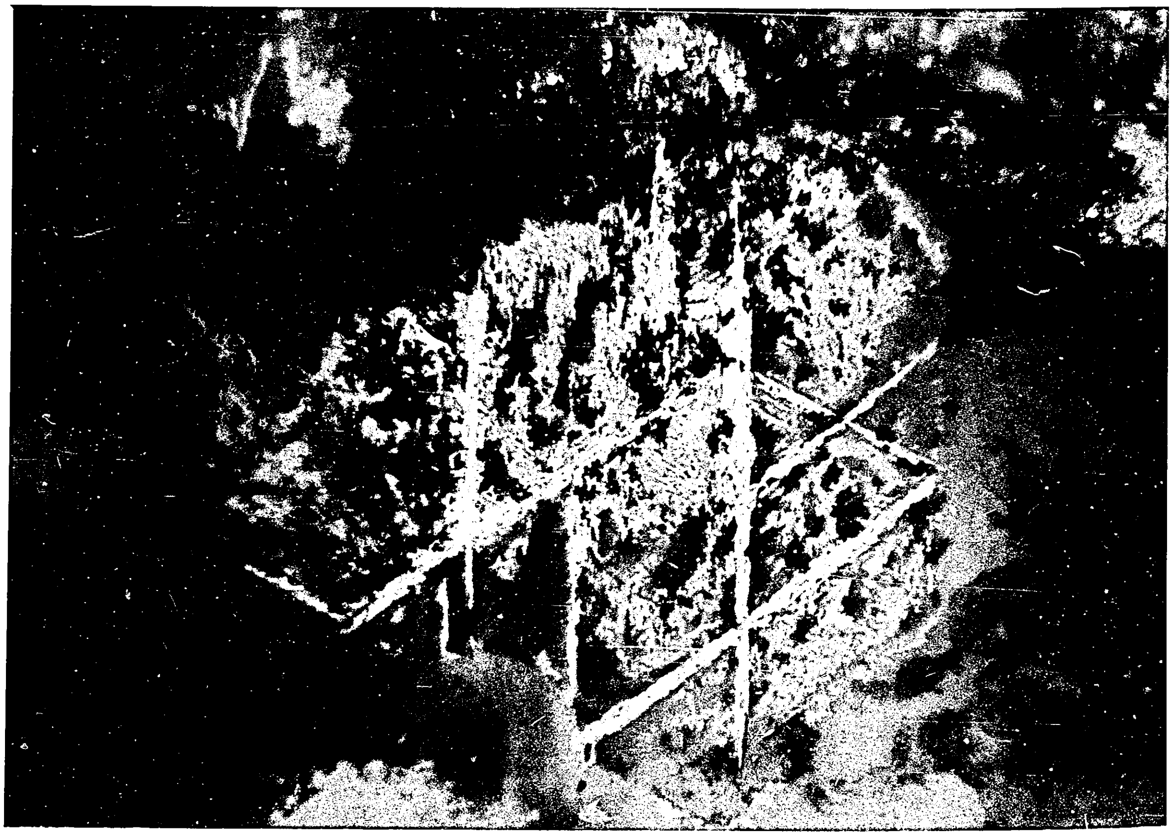


Figure 2.17.Variation of remanence direction across the southeen margin of Carrock Fell.



20μ

Figure 2.18. Complex exsolution of titanomagnetite in a sample from the Carrock Fell Gabbro Complex.

lamellae along the cleavage planes of hornblende (Figure 2.18).

2.4.3. Interpretation

To interpret these results the deformation history of the Complex must be known, so that any post-intrusion tilting can be removed. Firstly, it must be noted that the in situ direction ($D = 351^{\circ}$, $I = -15^{\circ}$, $\alpha_{95} = 10^{\circ}$, $N = 17$ Sites) is similar to the local geomagnetic field as inferred from other studies. This cannot be accepted as the best estimate of the mean remanence, because wherever pre-Carboniferous magnetization is inferred, the regional dip of the Lower Carboniferous must necessarily be applied. This tilt correction gives a mean direction of $D = 349^{\circ}$, $I = -19^{\circ}$, $\alpha_{95} = 10^{\circ}$, corresponding to a palaeomagnetic pole at Lat = 25°N, Long = 189°E, ($d\psi = 6^{\circ}$, $d\chi = 11^{\circ}$).

If the Carrock Fell Complex was originally a funnel-shaped intrusion, it might be surmised that flow-banded mineral lamination would be planar in any given sector. Tilt correction of site mean directions on the basis of mineral lamination has been performed on the data from the southern, and northern margins, and the Round Knott diabase separately. It leads to a significant decrease of precision, hence it may be concluded that the supposition was false.

Another alternative is that the Complex was originally a sub-horizontal 'sill' which has been subsequently tilted by about 70^{o} to attain its present attitude. The application of any large realistic tilt correction leads to mean remanence directions which are uninterpretable in terms of the Ordovician, or indeed any younger, geomagnetic field for the region.

The paleomagnetic results favour the view that the Complex was intruded essentially into its present position as a major dyke, subject only to slight Carboniferous warping. However, possible internal tectonic disturbance of the Complex must also be considered. The Drygill Shales of Caradocian age which immediately overlie the Complex are deformed into a small anticline whose axis is parallel to the Complex and whose limbs dip at 40^{o} and 70^{o} to the N and S respectively. No structures of this magnitude have as yet been mapped within the Carrock Fell Complex, and moreover, there is no reason to suppose that they exist. The prevailing view is that the Complex is younger than the

Drygill Shales, hence folding of the Shales need not be matched by corresponding deformation of the Complex. Possibly the original folding of the Shales was virtually symmetrical; later tilting to the north having produced the asymmetry. Hence only this later tilting may have affected the Complex. Tilt correction of approximately 15° due north, rotates the axial plane of the Drygill Shales anticline back to vertical, and also brings the mineral lamination of the Complex much closer to the vertical more in keeping with the proposed mode of intrusion as a dyke. Moreover, it also brings the mean remanence direction of the Complex closer to that of the adjacent Eycott Group. This is interpreted as the best estimate of the primary remanence direction for the Carrock Fell Complex, with a mean at $D = 351^{\circ}$, $I = -29^{\circ}$ ($k = 13$) corresponding to a virtual geomagnetic pole at Lat = 19°N, Long = 184°E ($d\psi = 6^{\circ}$, $d\chi = 11^{\circ}$).

Of all the analyses, this is the one with maximum precision of $k = 13.1$, nevertheless this is rather low by comparison to the Binsey Formation ($k = 29$), and the High Ireby Formation ($k = 25$), or with large gabbroic complexes e.g. Bushveld, $k = 68$ (GOUGH and VAN NIEKERK 1959), Stillwater, $k = 23$ (BERGH 1970), Freetown, $k = 43$ (BRIDEN, HENTHORNE and REX 1971).

One possible explanation is that distinct pulses of magma were intruded over a 'long' time interval. The presence of chilled margins between successiv sheets within the Gabbro Complex (EASTWOOD et al. 1968) indicates that the time between successive injections of magma was sufficient for consolidation of the previous phase. There are two possible causes for this low precision. Firstly, it is possible that the low precision provides an estimate of Ordovician secular variation, using the method proposed by Gough, Opdyke and McElhinny (1964), this gives an estimate of approximately $\Delta = 22^{\circ}$, which closely agrees with postulated equatorial secular variation estimates (IRVING 1964). A second plausible cause of dispersion would be that a later intrusion of magma might distort previously intruded and consolidated material and that such distortions are not accurately compensated for by the simple tilt correction. The data from the southern and northern margins of the Complex have negative magnetic inclinations, while the few results closer to the centre of the Complex (and Round Knott) have a shallow positive inclination (Figure 2.17). The petrological and magnetic discontinuitie at sites 19 and 52, and the sudden change of inclination between sites 51 and 52. With the small amount of data available it is impossible to decide whether the low precision and zonation of susceptibility, S.1., and remanence direction result from secular variation, magnetic and/or silicate mineralogy, internal deformation during multi-phase injection - or a combination of these factors.

Finally the uppermost Eycott Group of late Llanvirn age defines an upper age limit for the Carrock Fell Complex although time must be allowed for the intervening period(s) of deformation. The markedly different directions from lower Silurian rocks from Britain (BRIDEN, MORRIS and PIPER 1973) indicates a minimum age for the Complex. On purely palaeomagnetic grounds a best age estimate for the Carrock Fell Complex is Caradocian or Ashgillian (Chapter 5).

2.5 Diabase dykes intruding the Eycott Group

As shown on Figure 2.3 the Eycott group has been intruded by a number of diabase dykes (EASTWOOD *et al.* 1968). Their uniformity of trend (E-W), petrological similarity, and the presence of a similar set of dykes in the Carrock Fell Complex has been used to suggest that the dykes represent the last phase of intrusion of the Carrock Fell centre. However, there is no direct geological evidence for their age of intrusion. Six sites were collected from four separate dykes outcropping at Carrock Beck, Linewath, and Hegle End.

All sites have statistically significant total NRM which is grouped around D = 17°, I = $+75^{\circ}$ k = 33 (*in situ*) . Variation of site mean intensity is small ranging from 0.68×10^{-3}G to 0.31×10^{-4} with a logarithmic mean at 0.92×10^{-4} G. Upon progressive a.f. demagnetization all samples showed little direction change with a moderate and uniform Stability Index.

Within-site precision of all the sites increased after a.f. cleaning, with $k > 38$ for all sites except site 64, which is only based on four samples. Cleaning reduced the overall precision from k = 33 to k = 25, and slightly changed the mean direction to D = 14°, I =+66° (<u>in situ</u>) corresponding to a virtual geomagnetic pole at Lat = 80° N, Long = 116° E ($d\psi$ = 19° $d\chi$= 23°). The only apparent geological constraint on the age of intrusion is that the dykes do not intrude the local Carboniferous. Because of this uncertainty, samples from sites 62 and 65 were dated by K/Ar, they gave ages of 290 ∓4 my. and 350 ∓ 5 my. respectively (S.R. CHARLTON personal communication 1973).

The <u>in situ</u> remanence direction of the dykes most closely resembles results from the Tertiary dyke swarms of Britain (ADE-HALL <u>et al</u> 1971). Moreover, the rock is characterised by 'soft' magnetic remanence, low Stability Factor (WILSON <u>et al</u> 1968), low deuteric oxidation, and high within-site precision similar to this collection. For any proposed pre-Carboniferous remanence, a corresponding tilt correction must be applied. In every case this leads to a mean direction, which in terms of Palaeozoic palaeomagnetism, can only be interpreted as anomalous. Further discussion of a possible anomalous remanence directions is given in Chapter 5. If this anomalous field interpretation is untenable, then an explanation must be sought in the rock's magnetic properties. The possibility that the NRM is totally of VRM or IRM origin cannot be excluded until the mean grain size, oxidation state, and most important the time stability of these rocks has been established.

2.6 The Cockermouth Lavas

The basal Carboniferous succession of the northern Lake District is marked by a locally derived pebble conglomerate, which attains a maximum thickness of 30 m., where it unconformably overlies the Skiddaw Slates. Conformably overyling the basal beds are some basaltic lava flows. The lava is highly vesicular, and in parts highly weathered. Five sites were collected from a section outcropping near Wood Hall, Cockermouth.

All sites have significantly grouped total NRM. Although the overall mean of both the in situ and the tilt corrected site mean directions is non-significant. For most pilot specimens, progressive demagnetization produced an initial large intensity decay and direction

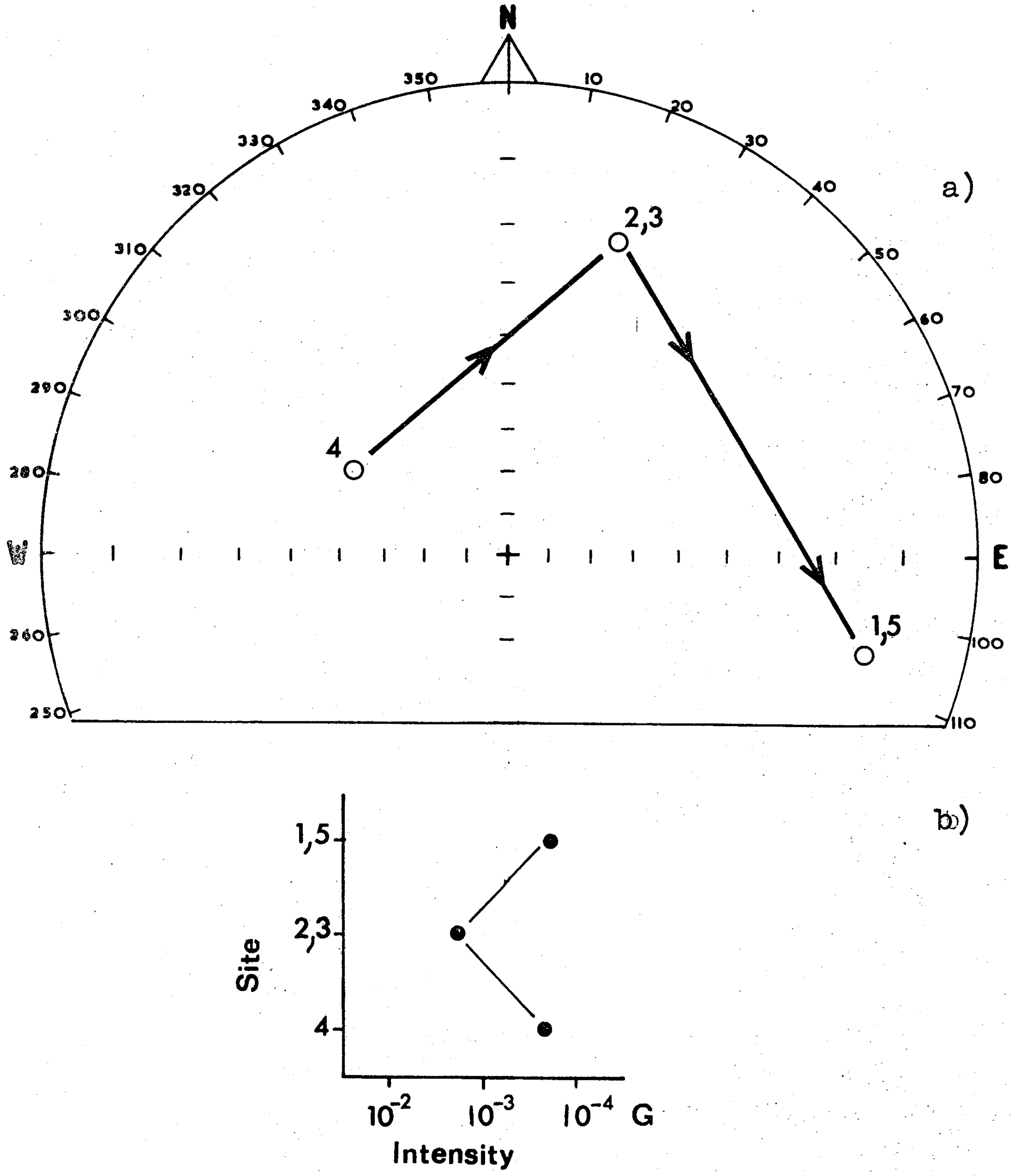


Figure 2.19. The variation of remanence direction (a), and intensity (b) with stratigraphic level.

change, with further treatment intensity decayed regularly, and direction changed little An exception was the specimen from site 2, this exhibited large direction changes and regular intensity decay throughout treatment. After a.f. cleaning all sites are again significant (Table 2.15).

Both the in situ and tilt corrected means remain non-significantly grouped. The lavas appear to record three groups of directions, which changes with stratigraphic level (Figure 2.19). The lowest lava (site 4) has a mean remenance at D = 299^{o}, I = -49 (tilt corrected). The second group is formed of sites 2 and 3; mean direction D = 21^{o}, I = -23^{o}. Sites 1 and 5 (the third group) are from the highest stratigraphic level in the lavas, lying immediately below the Carboniferous limestone succession, has a mean direction, D = 105^{o}, I = -13^{o}. Only group 2 is similar to known Lower Carboniferous geomagnetic field directions (EVERITT and BELSHÉ 1960). As the lavas only provide spot readings of the ambient field at the time of rock formation, the first possible explanation of the groups 1 and 3 remanence directions is secular variation. Unfortunately this would imply polar oscillations of a large magnitude, for which there is no other palaeomagnetic evidence. Secondly, the directions may be recording a polarity transition.

The group 2 sites have the highest site mean intensities, while the intensities of groups 1 and 3, is approximately a tenth of this. The directional difference between groups 2 and 1 is mainly in inclination while between groups 2 and 3 it is mostly declination (VAN ZIJL <u>et al.</u> 1962, COE 1967). Because of the small number of sites in this study, further collections are necessary to establish the individuality of the separate directions.

2.7 Summary and Conclusions

Palaeomagnetic results are reported from the Lower Ordovician Eycott Group, the Borrowdale Volcanic Group and the Carrock Fell Gabbro Complex. The mean stable remanence direction of the Eycott Group is $D = 0^{\circ}$, $1 = -43^{\circ}$, $\alpha_{95} = 6^{\circ}$ from 29 sites (dip corrected). Simple tilt correction gives a fold test significant at the 99% level. The

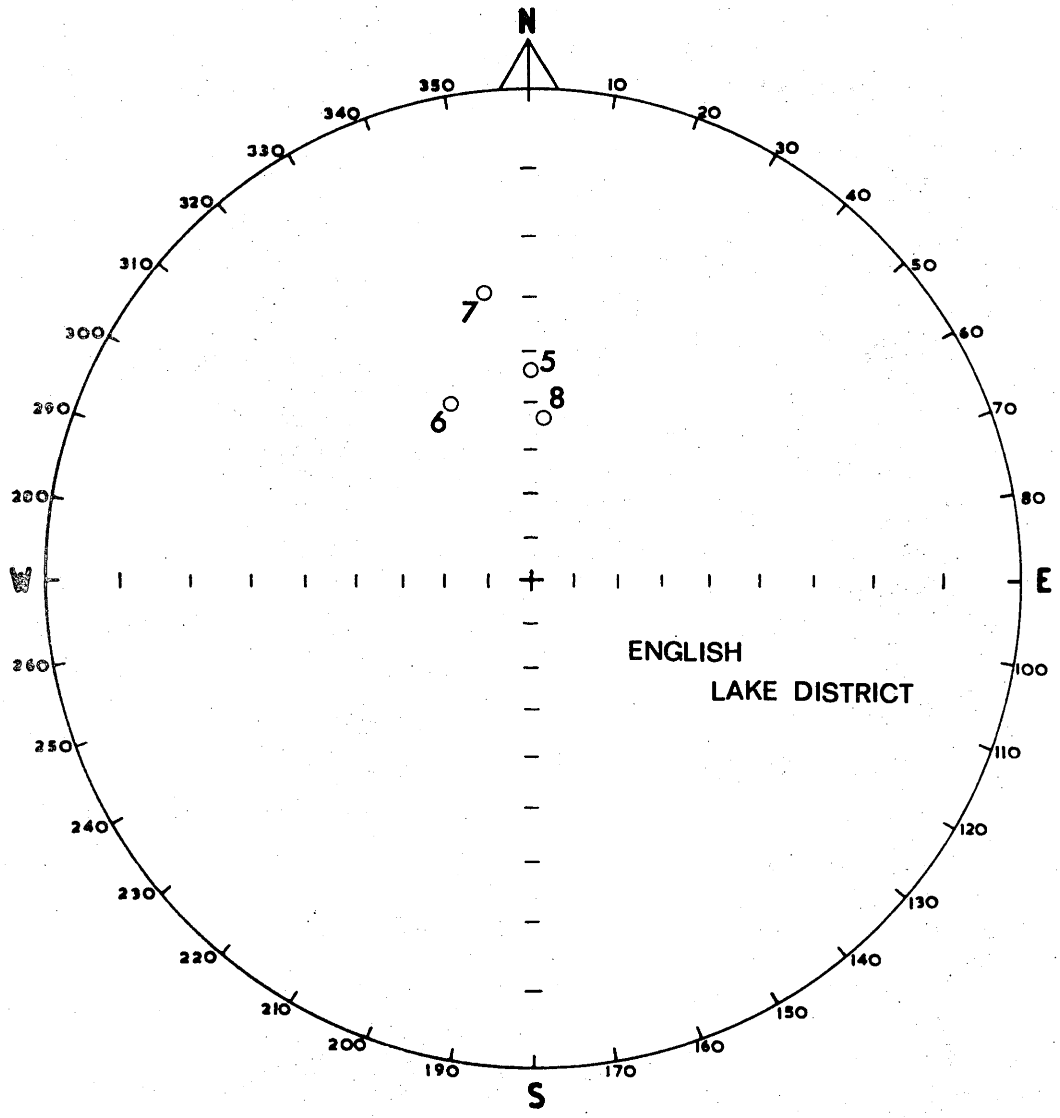


Figure 2.20. Remanence directions from the Lake District; the Eycott Group (5), the Borrowdale Group (6), Carrock Fell (7), and the Stile End dyke (8).

Borrowdale Volcanic Group carries two stable remanence directions, (a) principal group with a mean direction at $D = 338^{\circ}$, $I = -46^{\circ}$, $\alpha_{95} = 10^{\circ}$ (dip corrected), from twelve sites, which is supported by a fold test significant at the 99% level, and (b) an anomalous group with a mean direction $D = 337^{\circ}$, $I = +80^{\circ}$, $\alpha_{95} = 16^{\circ}$ (*in situ*). The Carrock Fell Gabbro Complex has a mean remanence best interpreted as originating in the Ordovician, mean direction $D = 351^{\circ}$, $I = -29^{\circ}$. $\alpha_{95} = 10^{\circ}$ from 17 sites. Minor studies from dykes show that intrusives of both Upper Ordovician and possibly Devonian age occur in the Lake District. All these data are based on partial a.f. demagnetization. All Ordovician studies have the same polarity. For the major studies the corresponding virtual geomagnetic pole positions are, Eycott Group, Lat = 10°N, Long = 176°E, ($d\psi = 5^{\circ}$, $d\chi = 8^{\circ}$) Borrowdale Volcanic Group, Lat = 6°N, Long = 196°E ($d\psi = 8^{\circ}$, $d\chi = 13^{\circ}$), and the Carrock Fell Complex, Lat = 19°N, Long = 184°E ($d\psi = 6^{\circ}$, $d\chi = 11^{\circ}$).

The principal contributions of this palaeomagnetic study to the geological evolution of the English Lake District are; first, to demonstrate that the Carrock Fell Complex was intruded as a dyke-sheet subject only to minor tilting, and that it was intruded at some time during the interval Caradoc-Ashgill. Secondly, each volcanic episode was followed by a period of deformation. All folding in the volcanics is simple and open, and was produced prior to the end of the Ordovician. Thirdly and most importantly, although the end-Silurian deformation produced tight folding in the relatively incompetent high level Silurian sediments, it merely produced simple tilting and intense cleavage belts in the older, stratigraphically lower, and more competent volcanic rocks. Finally, from the small amount of data reported here, the contact between the Borrowdale Volcanic Group and the underlying Skiddaw Slates is best interpreted as a thrust.

CHAPTER 3

COUNTIES MAYO AND GALWAY, EIRE

3.1 Introduction

The South Mayo Trough has a unique position in the British Caledonides; it is the only place where the structural relationships of Dalradian, Ordovician, and Silurian rocks can be studied in a small area (Figure 3.1). The Dalradian acted as the basement upon which extensive deposition took place (STANTON 1960, McKERROW and CAMPBELL 1960, DEWEY 1961, 1963, 1967). Both the southern and the northern margins of the Mayo Trough are largely fault-controlled. In the south the Silurian overlaps onto the Dalradian hence masking the contact between the Ordovician and the underlying Dalradian. During the Ordovician detritus was derived mainly from the south in Connemara, while most of the Silurian sediments were derived from a northerly provenance. (DEWEY 1963, McMANUS 1967, PIPER 1967).

In the Connemara Dalradian rock type varies from high grade migmatites, through metaquarzites and marbles to ultrabasics (LEAKE 1970). Deformation of the Dalradian is much more complex than in the adjacent Lower Paleozoics. Most of the southern margin of the Connemara block is bounded by the Galway Granite (BURKE 1957, WRIGHT 1964) which LEGGO, COMPSTON and LEAKE (1966) have dated at 384 ± 1 my. An exception

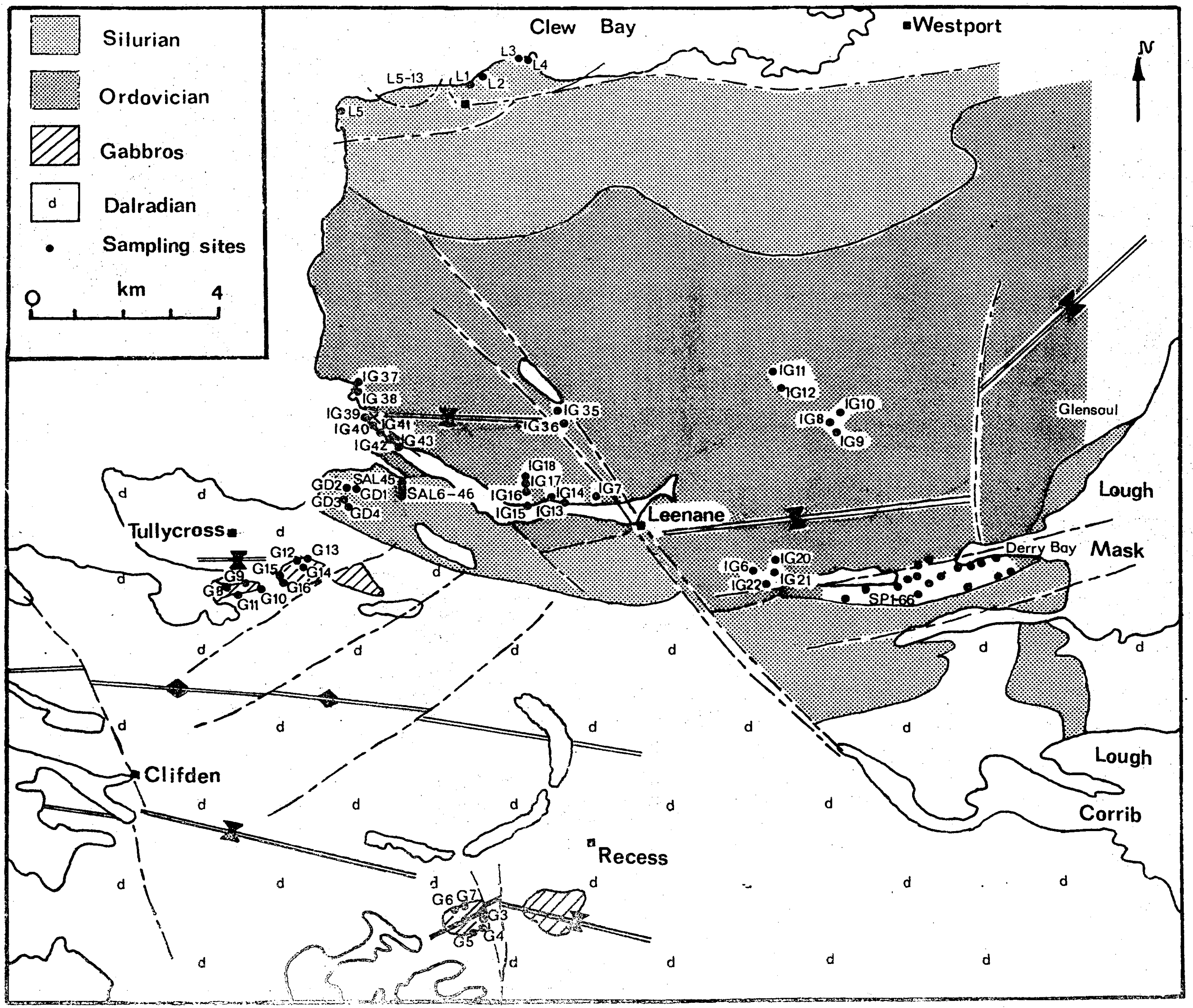


Figure 3.1

Geological map of Co.Mayo and Co.Galway, Eire.

Sampling locations are;

G -Connemara gabbros

IG -Mweelrea ignimbrites,

SP -Spilites, Lough Nafooey

GD -Granodiorate,

Sal -Salrock Formation

L -Louisburgh.

to this is an outcrop on the extreme southern point of Connemara where there are a series of Ordovician(?) volcanics which McKIE and BURKE (1955) have compared to the basal Ordovician of the Mayo Trough.

Within the Trough the Ordovician strata shows marked north-south thickness and facies variations, in the north 12,000m. of turbidites, slates, arkoses and conglomerates are the lateral equivalents of less than 3,000m. of shallow water sediments and volcanics. Most workers have dated the oldest fossiliferous rocks as Arenigian (GARDINER and REYNOLDS, 1909, 1910, 1912, 1914, STANTON 1960, McKERROW and CAMPBELL 1960, DEWEY 1963). Recently, however, this view has been disputed. BERRY (1968) re-examined the collections of GARDINER and REYNOLDS from Glensaul and Kilbride, considered the best correlation was with the Whiterockian of Texas, and concluded a Llanvirnian age. This differing correlation has been strongly contested by DEWEY, RICHARDS and SKEVINGTON (1970), who re-affirmed their belief that the majority of fossilerous rocks are Arenigian. The conflict remains undecided. After recent mapping G. H. WILSON (personal communication 1973) has questioned the validity of the accepted Ordovician stratigraphy. The position and relationships of the Lough Nafooey spilites within the Mayo trough presents many correlation problems.

Structural evolution of the Trough during the Ordovician was mainly controlled by a conjugate fault system. It has been suggested that this initially developed along an east-west trend probably associated with spilite eruption (e.g. Doon Rock, Derry Bay, and Letterbrock faults, DEWEY 1962); it was followed by movement on the NW-SE Maam wrench faults (STANTON 1960). Prior to the deposition of the Silurian sediments, strong E-W trending concentric folding of the Ordovician took place (e.g. Mweelrea syncline). At the same time the Upper Dalradian was thrust southwards over the Lower Dalradian in the Highland Boundary Fault zone (DEWEY and PHILLIPS 1963).

The lowest Silurian rocks are of Upper Llandovery age; basal beds formed of terrestrial breccias and coarse sandstones, unconformably overlie Dalradian schists. Again major E-W trending faults controlled sedimentation rates, and topographically defined the margins of the turbidite basins. In the east of the area the Silurian beds are folded into wide synclines and narrow faulted anticlines, while in the west steep faults replace the folds, the beds having a uniform northerly dip. Thrusts and steep reverse faults overriding from the north occur with large NW tear faulting. From Joyces Country in the south, to the

Highland Boundary Fault Zone in the north, there is a general northward increase of metamorphic grade and intensity of deformation.

The only published paleomagnetic result from the Trough is that of DEUTSCH (1969) from the Mweelrea ignimbrites. When compared to results of similar age from England (BRIDEN, MORRIS and PIPER 1973) this result appears anomalous. The wide range of rock types and ages in Connemara make it possible to investigate both the vertical and lateral extent of this anomaly.

3.2 The South Connemara Series

The most southerly point of Connemara is formed of Lower Ordovician(?) volcanics. McKIE and BURKE (1955) have dated them on purely lithological grounds as Arenig as their local stratigraphy closely resembles the basal Ordovician of the Mayo Trough (CARRUTHERS and MAUFE 1909, GARDINER and REYNOLDS 1909, 1910, 1912, and 1914).

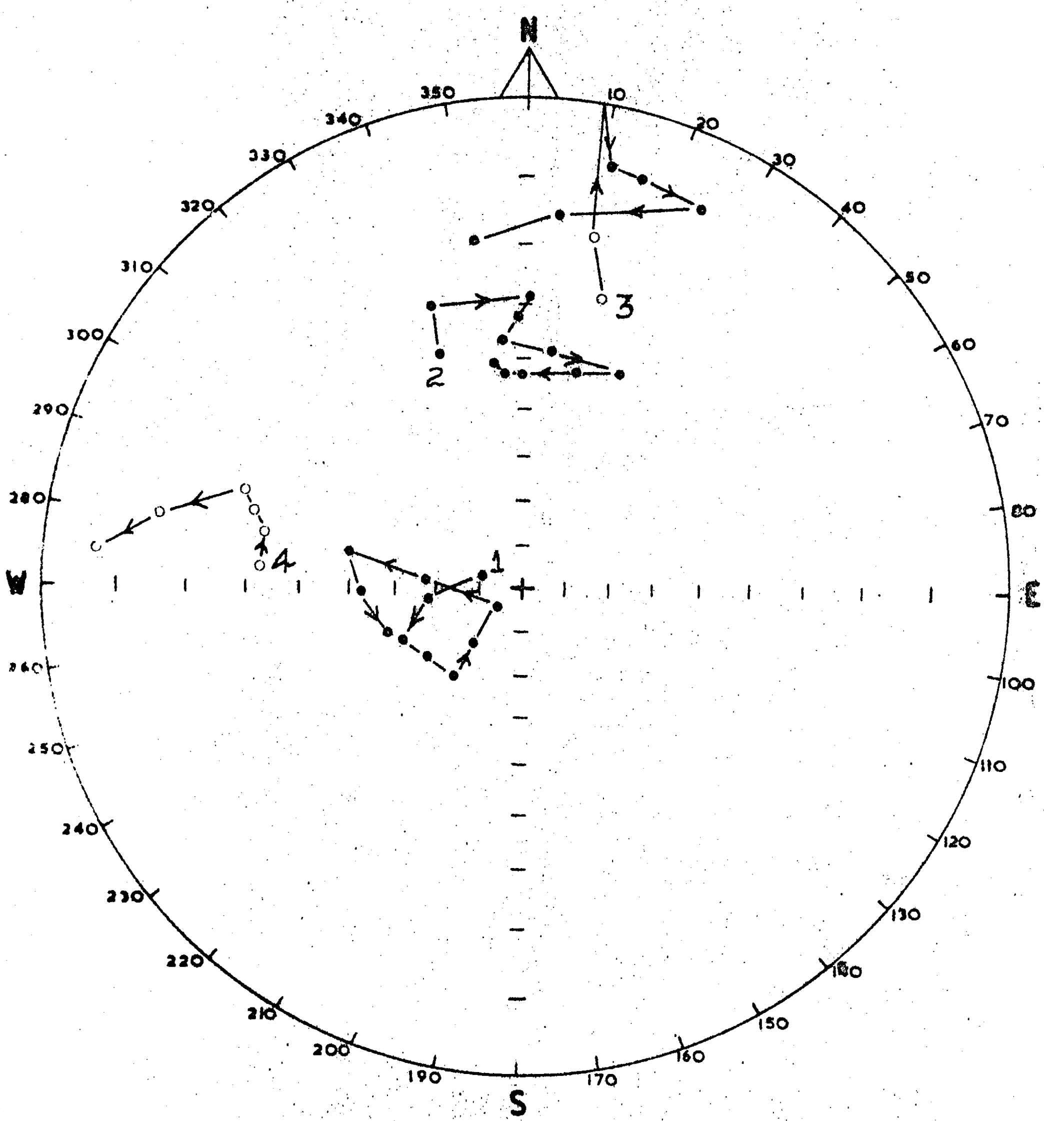
The beds have been overturned, they dip steeply to the south, while facing to the north. Successive contact metamorphic zones produced by the Galway granite follow in sequence from the granite contact, folding of the spilites is therefore dated as pre-end Silurian (i.e. pre-Granite intrusion). Most of southern Connemara is formed by the granite, whose southerly contact may be in Galway Bay. It is possible therefore that the South Connemara Series is merely a roof pendant of the granite, implying that both rotation and remagnetization may have taken place.

It was intended that sampling be limited to the Lower Basic Group, but because of the difficulty of discriminating between fine-grained lava and reworked volcanic material in the field, some sites were collected in the sediments. All samples were collected by field drill and all orientations were made by sun compass. The dip, strike and location of each site was noted by Dr. P. W. G. Tanner.

Three of the twelve sites sampled yielded non-significantly grouped total NRM (Table 3.1). of these only sites 1, 5, 8, and 12 have remanence significantly grouped at the 99% level (WATSON 1956 b). The <u>in situ</u> mean remanence direction of the nine sites is D = 230°, I = +54°, k = 2.2, tilt correction increases the precision to $k = 2.4$ and moves the mean direction to $D = 353^{o}$, $I = +3^{o}$ (Table 3.2).

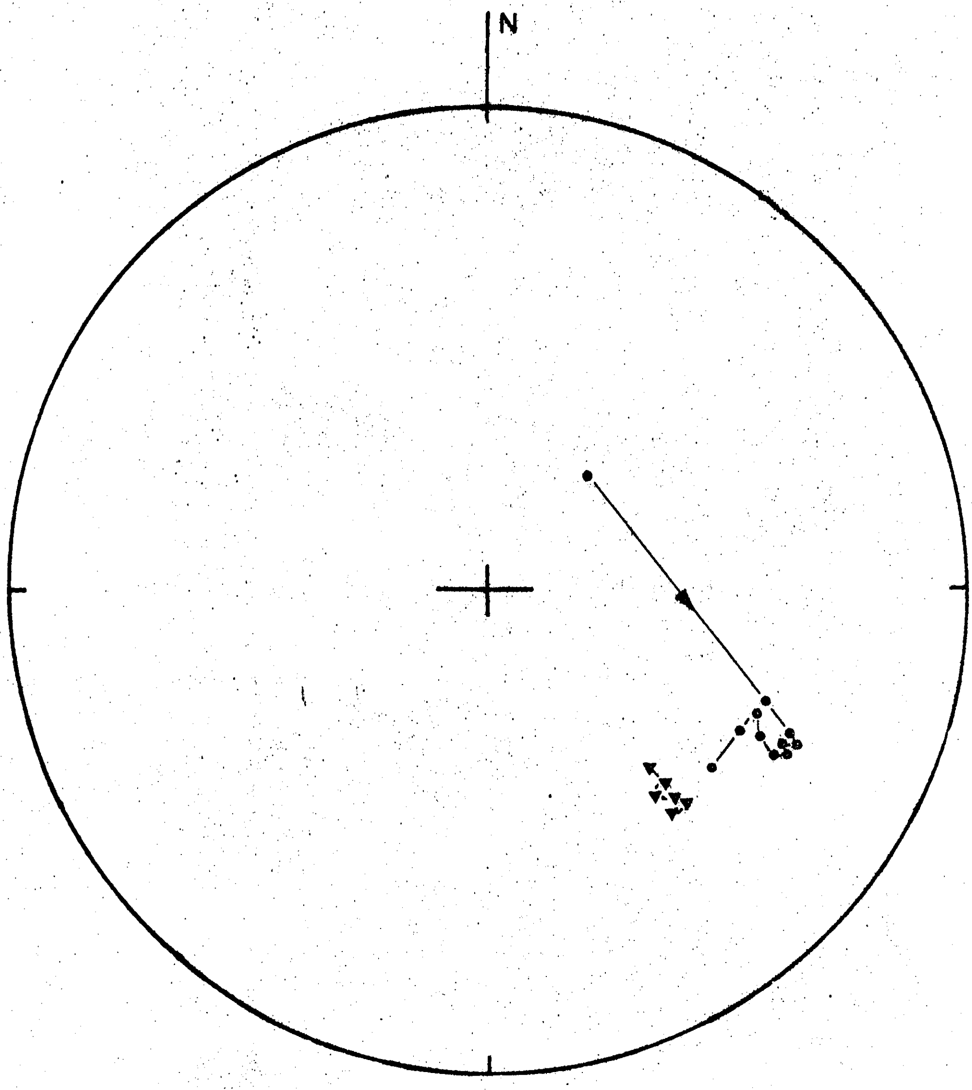
NRM intensity shows wide variations both within and between sites. The overall mean is 0.25×10^{-3}G while the range is from 0.24×10^{-6} (site 3) to 0.21×10^{-2}G (site 5), site 1 is a good example of within-site variation, with a range of 0.13×10^{-2} to 0.93×10^{-6}G. All polished specimens examined (except those from sites 3 and 4), contained unexsolved skeletal and euhedral grains of titanomagnetite. Pyrite a common accessory occurred as large idiomorphic crystals ($> 50\mu$) commonly intergrown with the titanomagnetite. This compares closely with the results of WATKINS, PASTER, and ADE-HALL (1970) on the magnetic and opaque petrology of a recent pillow lava. Polished specimens from sites 3 and 4 contained very little opaque material most of which was fine-grained hematite, this together with the fine lamination visible in hand specimen indicates that these rocks are of sedimentary origin.

The lavas and the sediments exhibited different a.f. demagnetization characteristics (Figure 3.2). After a.f. cleaning seven sites had significantly



a)

Figure 3.2. Variation of remanence direction upon a.f. demagnetization.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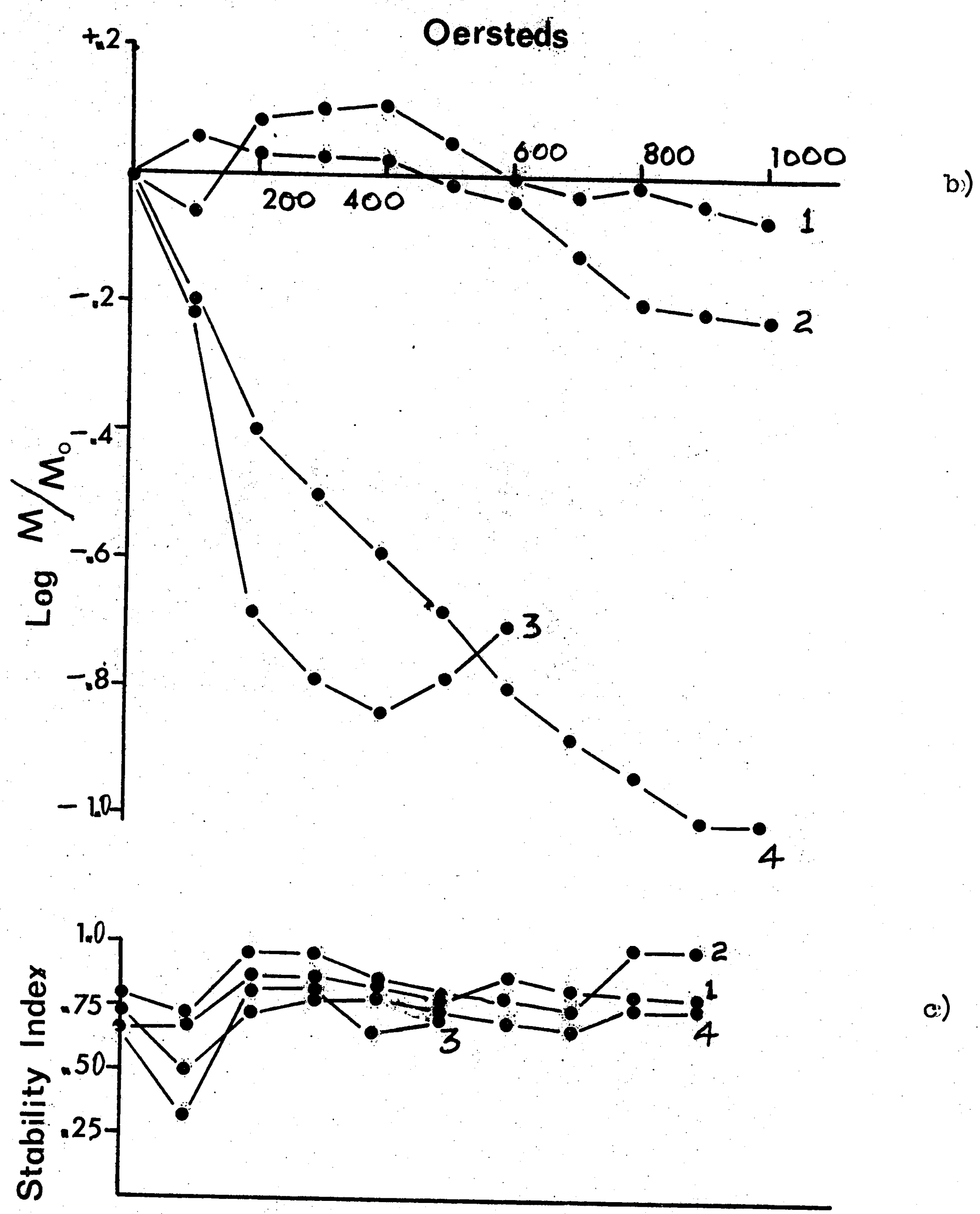


Figure 3.2. Variation of remanent intensit y (b) and Stability Index (c) upon a.f. demagnetization. Sediments 1,2 lavas 3,4.

grouped remanence, all with the same polarity (Table 3.3). The site 3 result is not included in any calculation of an overall mean for the following reasons. First, polished samples from this site indicated a detrital origin for the rock, hence remanence is probably not contemporaneous with the other sites at this collection. Secondly, the pilot sample exhibited only irregular intensity shifts upon demagnetization. Thirdly, the specimen intensities were all close to the measuring limits of the spinner magnetometer, and finally, applying the test of WATSON (1959 a) the site mean direction is significantly different from the other significant sites.

The <u>in situ</u> mean remanence direction based on six sites is D = 196°, I = +54°, k = 2.2, the tilt corrected mean is D = 5°, I = +9°, k = 2.7. Tilt correction produces a small numerical increase of precision but does not constitute a significant fold test of remanence. Sites 1, 5, 9 and 12 have a mean remanence direction which is significantly different to that of sites 7 and 8 (WATSON 1959 a), which were collected from massively bedded volcanics, where the local dip was inferred from nearby outcrops. This discrepancy therefore may be due to inaccurate tilt correction. Although there is no repetition of strata, folding is more complicated than simple tilting

(B. E. LEAKE personal communication 1973). Hence another estimate of the mean remanence direction from the four best grouped sites of the South Connemara Series based on 23 samples is D = 293°, I = +83°, k = 6.1 (in situ), and D = 4°, I = -23°, k = 5.5 (tilt corrected). This tilt corrected direction is similar to other Ordovician results from Britain (BRIDEN, MORRIS and PIPER 1973). If this direction is primary then the contact between the Galway granite and the South Connemara Series is the southern limit of the granite, and moreover the Ordovician volcanics are not a roof pendant of the granite.

3.3 The Arenig pillow lavas, Lough Nafooey

3.3.1 Geology and sampling

It has long been thought that the basal Ordovician of the South Mayo Trough is a series of pillow lavas, with interbedded tuffs and felsite breccias but recently the location of these beds has been questioned both on stratigraphic and geochemical grounds. GARDINER and REYNOLDS (1912, 1914) dated the lavas as Arenig on the basis of graptolitic shales which occur as pockets within the lavas. While the unconformable contact between the spilites and the overlying sediments is well exposed along the southern shore of Lough Nafooey, the internal structure and stratigraphy of the spilites is less well known. GARDINER and REYNOLDS (1912, 1914) record only northerly dips in the lavas, although the degree of dip varies they do not show any large scale folding. DEWEY and McKERROW (unpublished map) on the other hand indicate a major E-W trending anticline in the spilites. It is possible that the detailed structure is much more complex, because for example, bedded cherts which directly overlie the lavas outcropping on Knock Kilbride have minor folds with near vertical axes, while in an adjacent block the beds dip regularly to the north.

Paleomagnetic sampling was by field drilling and hand sampling, orientation was by sun and/or magnetic compass. Wherever possible the local dip was measured; it was always to the north with tilt varying from 40^{o} to near vertical. Interbedding of fine grained tuffs and massive lavas made field identification difficult.

3.3.2. Paleomagnetic results and interpretation

In site mean calculations unit weight was given to each specimen. Five of the twenty-two sites visited had non-significant total NRM site means (Table 3.4). The in situ mean of the significant sites is D = 145°, I = +84°, k = 6.3; tilt correction gives a mean at D = 355°, I = +31°. As with the South Connemara Series large variations of intensity both within-and between-site are common. It is well known that position within an individual pillow can produce systematic variations of intensity, susceptibility, and oxidation state (WATKINS, PASTER, and ADE-HALL 1970, MARSHALL and COX 1971).

Standard a.f. demganetization techniques were applied; in cases where there was large within-site intensity variations two samples were treated. In general, although the demagnetization curves differed, the selected optimum field was very similar. A.f. demagnetization characteristics are summarised in Figure 3.3; significant points are (a) the regular and rapid decay of intensity up to 400 Oe., and (b) the distinctive intensity decay curves of sites 2 and 53 .

After cleaning fifteen sites have statistically significant remanence (Table 3.5), with an in situ mean of D = 195°, I = +64°, k = 2.5. Applying a

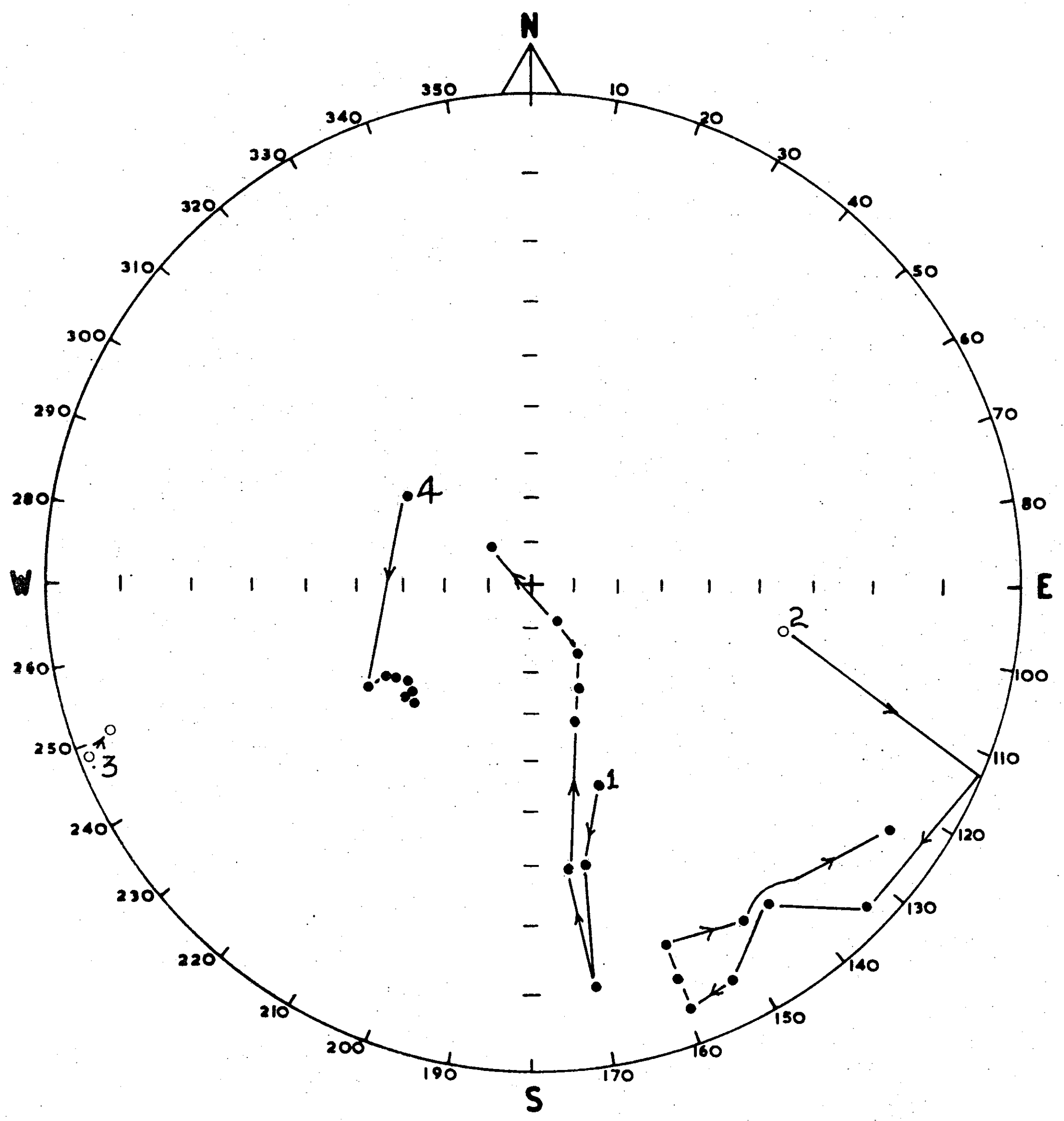


Figure 3.3. Variation of remanence direction upon a.f. demagnetization. Samples 3 and 4 are from the distinctive sites 2 and 53.

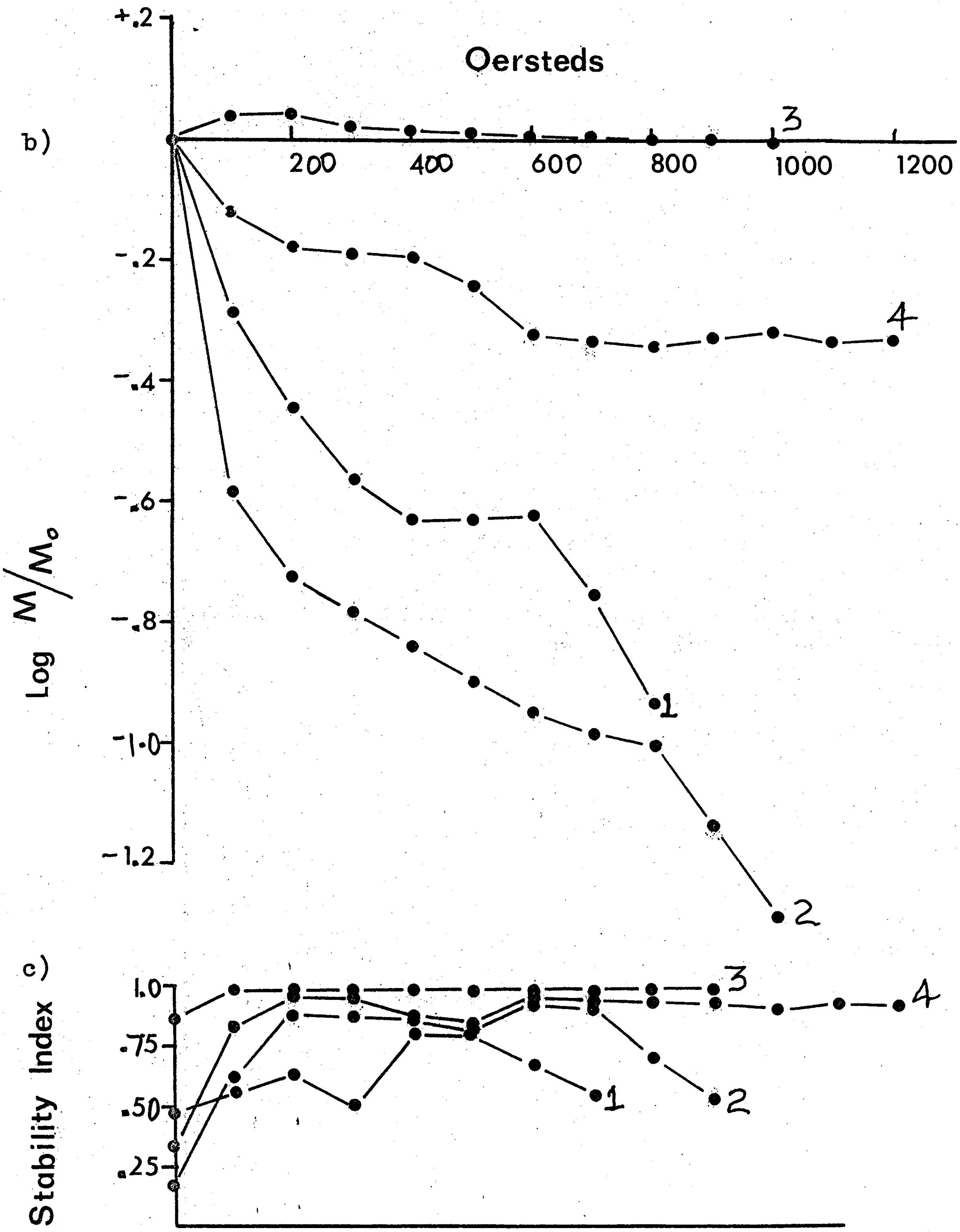


Figure 3.3. Variation of remanent intensity (b) and Stability Index (c) upon a.f. demagnetization.

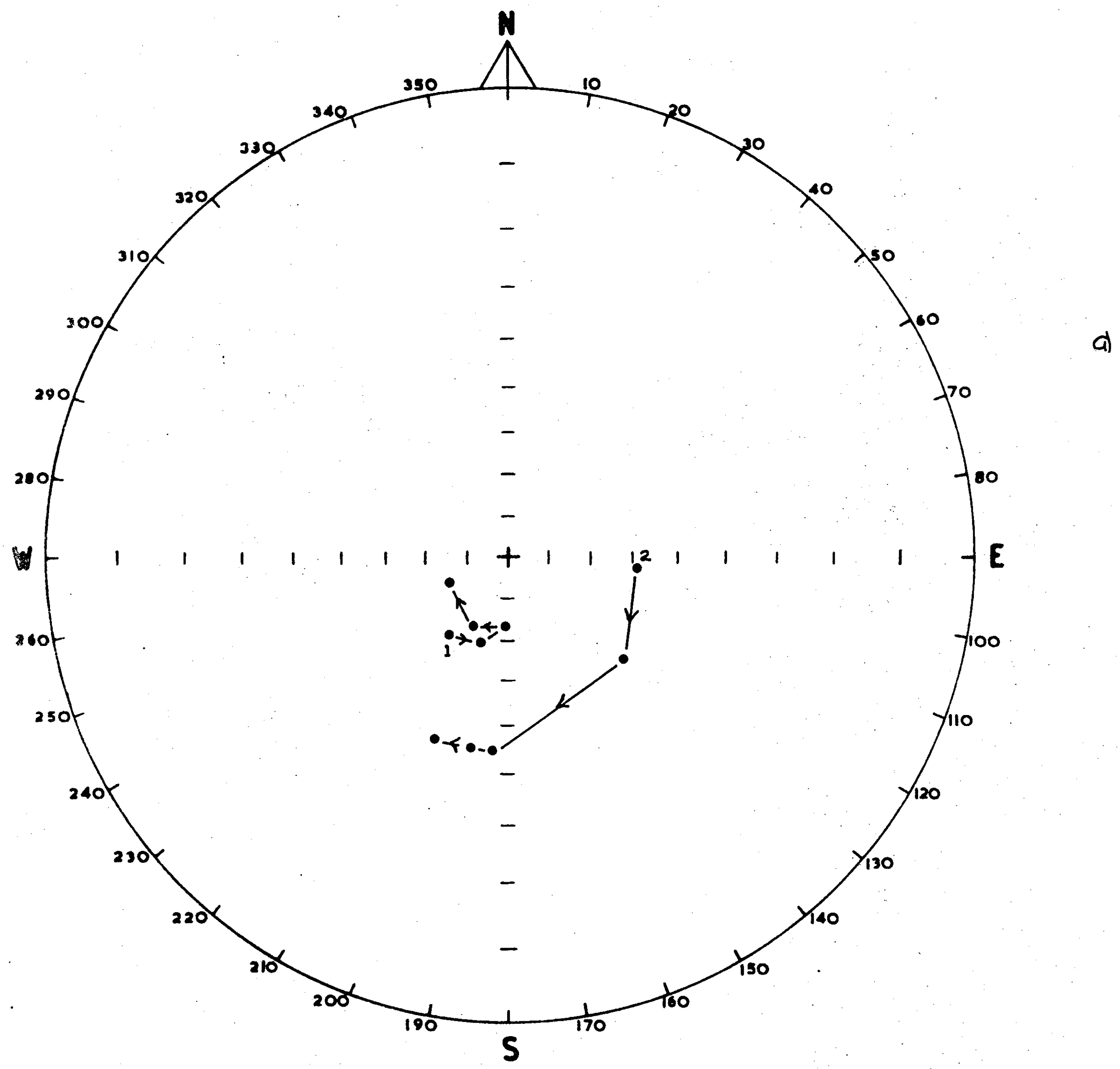


Figure 3.3(i) Variation of remanent direction(a), intensity (b),and Stability Index (c) upon a.f. demagnetization. Both samples are from the same site,1 is strongly magnetized, 2 is weakly magnetized.

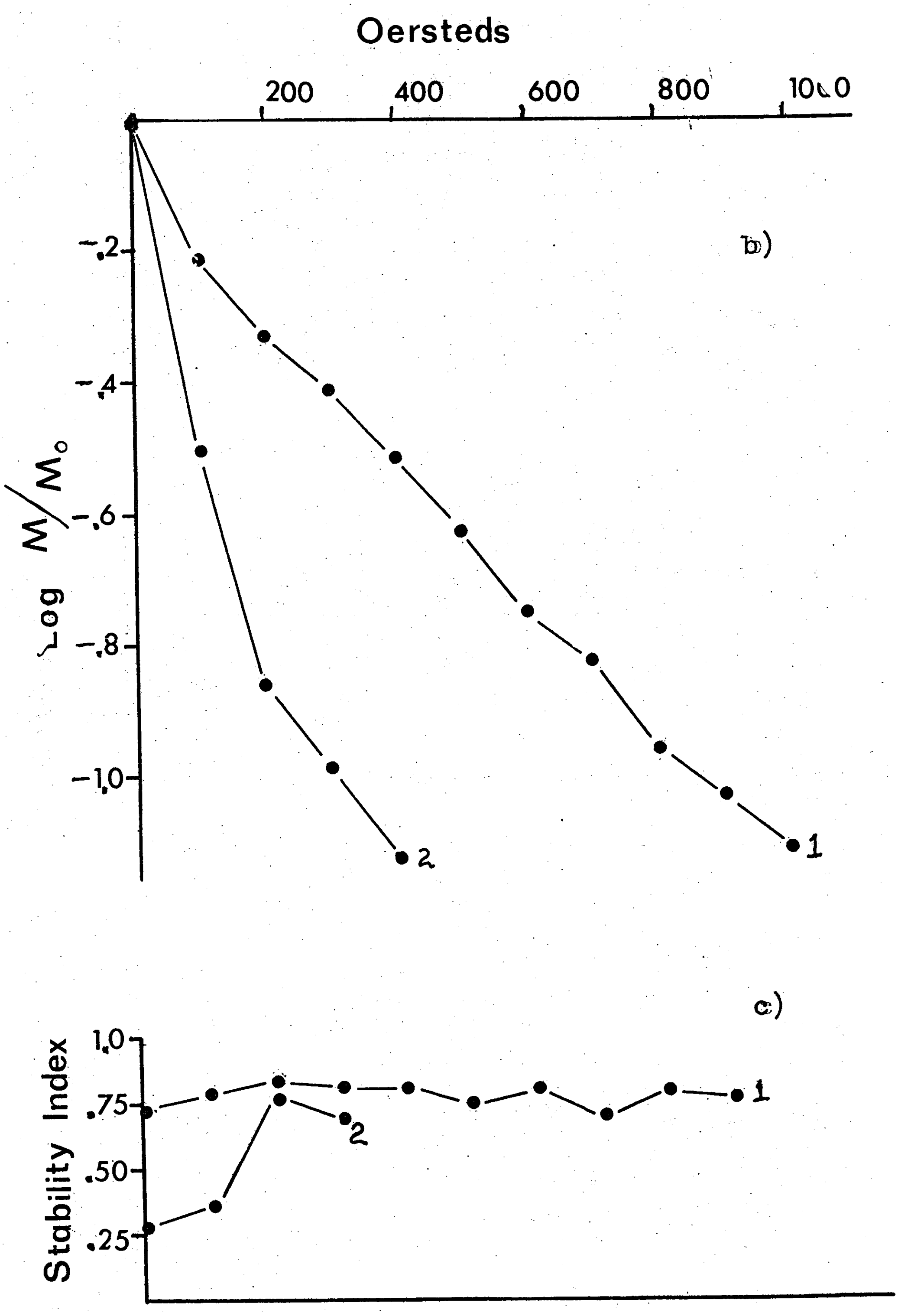


Figure 3.3(i), b) and c).

steep northerly tilt correction produces a mean of $D = 339^{\circ}$, $I = +36^{\circ}$, $k = 1.9$. Table 3.5 shows that sites 2, 4, 46, and 53 have remanence directions significantly different to the remaining sites. Calculating a mean for the two groups (Table 3.6) shows that the separation of the two <u>in situ</u> directions is 90°, while the tilt corrected directions are separated by 145°. This is indicative of primary remanence with dual polarity. The tilt corrected mean irrespective of polarity is $D = 4^{\circ}$, $I = +10^{\circ}$, $k = 5.5$, which corresponds to a paleomagnetic pole at Lat = 42°N, Long=165°E ($d\psi = 9^{\circ}$, $d\chi = 18^{\circ}$). Applying the tilt correction suggested by DEWEY and McKERROW (unpublished map) produces a marked decrease of overall precision. Hence, either their anticline does not exist, or sites have been collected from only the northern limb of the fold. As each site was located on the map of DEWEY and McKERROW at the time of sampling the latter suggestion seems improbable. This implies that the spilites are simply tilted steeply to the north, as are the spilites of Bohaun (McMANUS 1967), and Gorumna (McKIE and BURKE 1955).

The low precision ($k = 5.5$) of the final result is almost certainly due to inaccurate tilt correction. Many of the corrections are large ($>70^{\circ}$), hence it is possible that folding is either not purely cylindrical, or more complex than allowed for here, may be even requiring multi-stage tilt correction.

3.5 Mweelrea ignimbrites

DEUTSCH (1969), DEUTSCH and SOMAYAJULU (1970) and MURTHY and DEUTSCH (1971) have reported palaeomagnetic results from the mid-Ordovician Mwreelrea ignimbrites of the South Mayo Trough. They have shown that the ignimbrites have high magnetic stability and also, show by positive conglomerate and fold tests that the magnetization is pre-tilting. This magnetization is anomalous when compared to British rocks of a similar age (BRIDEN, MORRIS and PIPER 1973). Because this anomaly could have far reaching implications, it is important to check its validity.

3.5.1 Geological Outline

The area around Killary Harbour, Western Eire, where the Mweelrea ignimbrites outcrop has been mapped by STANTON (1960), McKERROW and CAMPBELL (1960) and DEWEY (1963). STANTON (1960) describes the generalised internal structure of the six ignimbrite bands noting that they typically exhibit green tuffaceous bases, highly welded-columnar jointed central portions and less well-consolidated tops. He correlates the thickness of green base with water depth at the time of ignimbrite formation, and infers a slight North-Westerly increase in water depth. This also supports the idea that depositional dips are very low and almost zero (WILSON personal communication 1972). Each ignimbrite sheet represents a sudden burst of igneous activity recording an instantaneous time plane over the depositional basis. The complex sedimentary environment is exemplified by the convergence in different parts of the region of bands 3 and 4, and 4 and 5. DEWEY (1963) showed that the grit wedge between ignimbrite bands 5 and 6 varies from 1600m. on the northern limb of the Mweelrea syncline in Central Murrisk to 60m. on the southern limb in Joyces Country. McKERROW and CAMPBELL (1960) working in Joyces Country, point out that in nearly every case the ignimbrite sheets increase in thickness towards the South-East and suggest a source area in that direction.

The most reliable evidence of age is given by WILLIAMS (1972) who suggests a mid-Llanvirn age for the ignimbrites on a brachiopod assemblage collected close to site 39. The results reported in this section are from twenty-five sites, collected from a much wider area than that reported by DEUTSCH and SOMAYAJULU (1970).

3.5.2. Total NRM and a.f. demagnetization

Within-site precision of total NRM directions is here estimated by FISHER (1953) analysis, giving unit weight to each specimen (Table 3.7) - a justifiable procedure because here, orientation errors are no greater than other sources of error incurred in the method. By this criterion only four of the twenty-five sites are non-significant at the 95% confidence level, (Watson 1956 b). The directions at 17 sites form a major group around $D = 139^{o}$, $I = +42^{o}$; four sites, all from band 3 form a minor group near $D = 330^{o}$, $I = +45^{o}$. There is no systematic intensity variation between bands, and the intensity range is large - from 6.7×10^{-6}G to 3.5×10^{-3}G.

Progressive a.f. demagnetization characteristics agree with the results of DEUTSCH and SOMAYAJULU (1970). Cleaning merely removes low-coercivity components, orientated close to the present geomagnetic field (Figure 3.4).

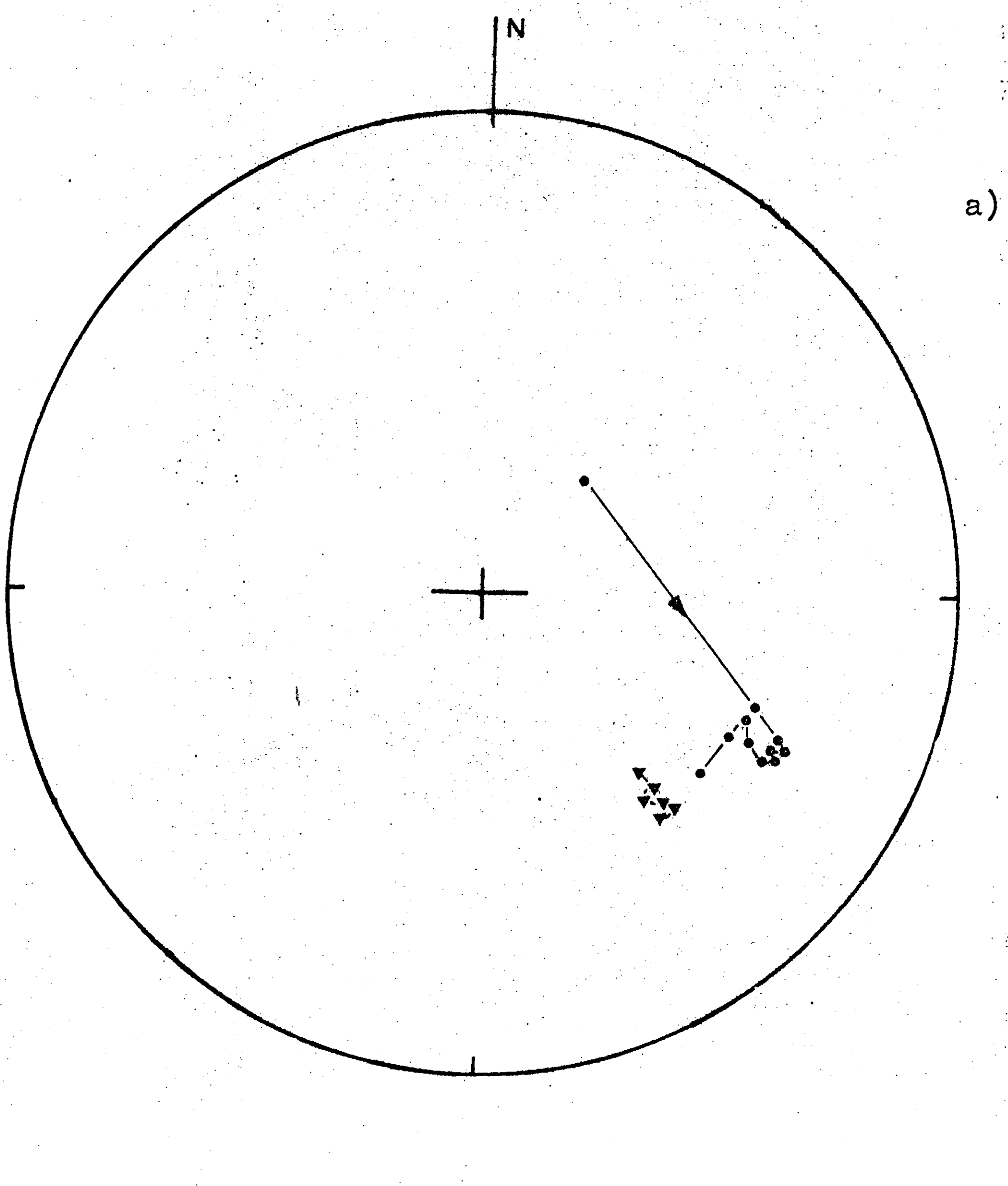
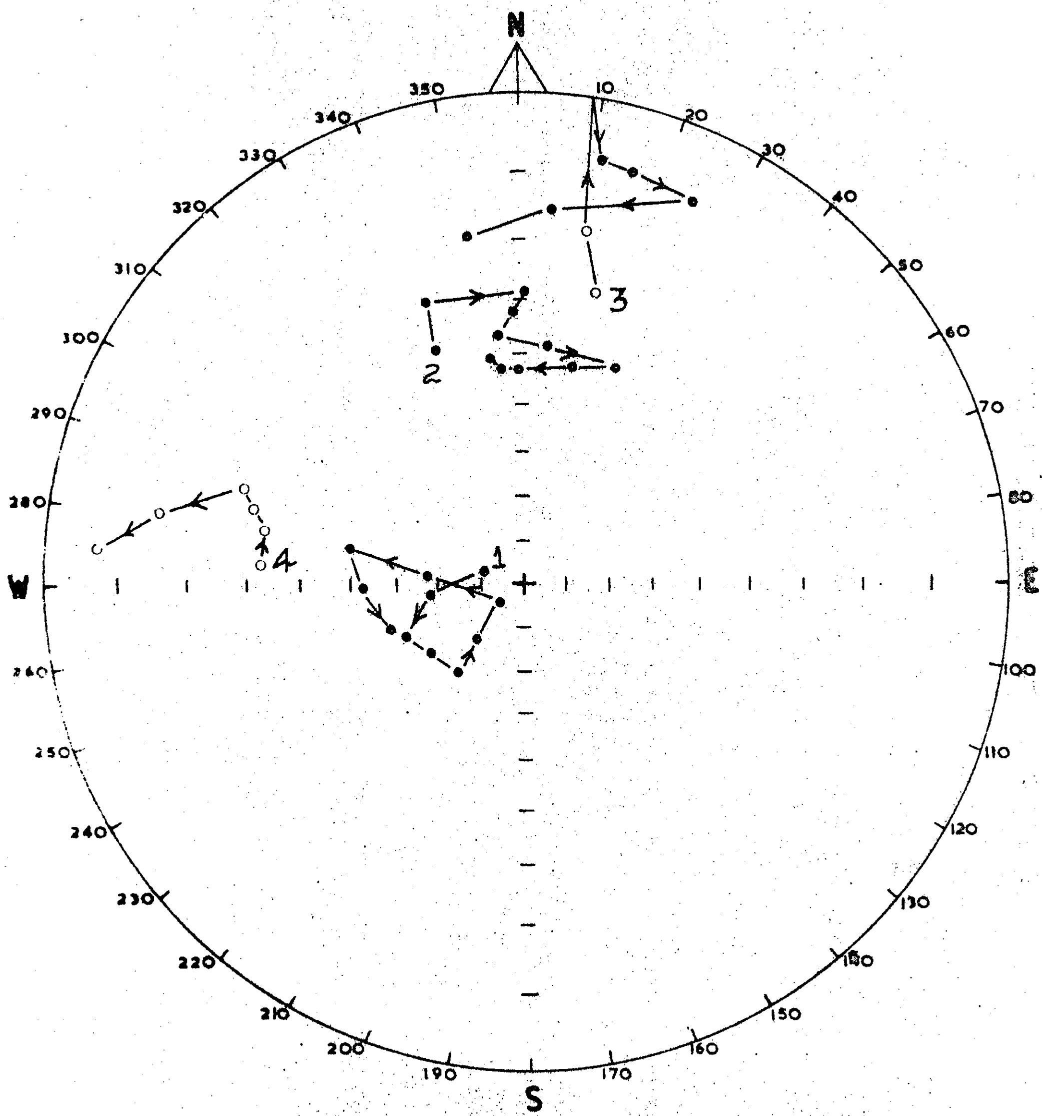


Figure 3.4. Variation of remanence direction (a), intensity (b), and Stability Index (c) upon a.f. demagnetization.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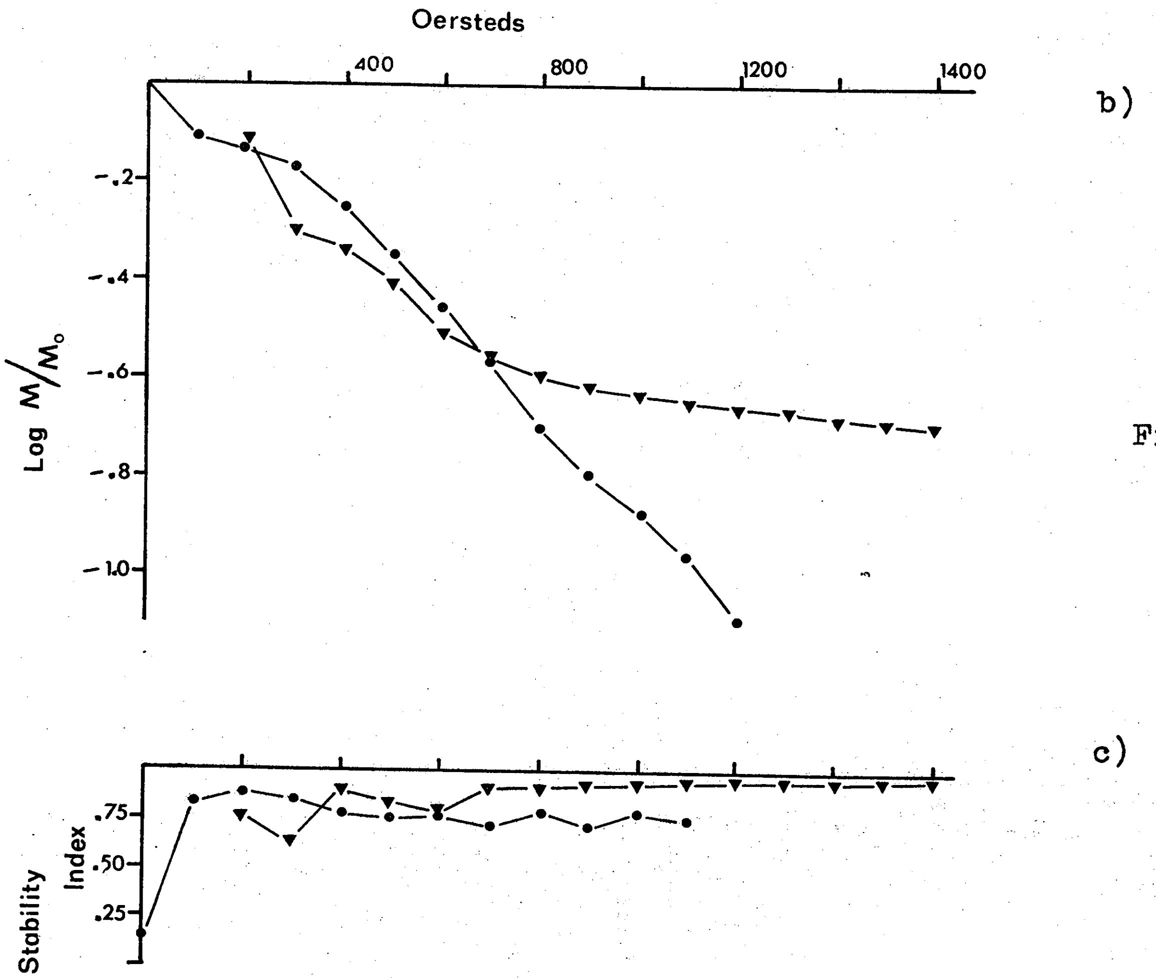


Figure 3.4. b) and c).

High stability of direction and intensity suggests the presence of haematite (N.D. WATKINS, in DEUTSCH and SOMAYAJULU (1970)), in addition to the titanomagnetite which is the principal remanence carrier.

3.5.3. Magnetic Cleaning

Of the twenty-five sites reported in this study thirteen were cleaned at 200 Oe., five at 300 Oe, and the rest in slightly higher fields. Because it was not possible to select an optimum field for site 43, it is discounted from further analysis. After cleaning twenty-three sites are significant, sites 17 and 43 not responding to treatment. Sites 6, 7, 8 and 12 which were well defined prior to cleaning show little or no change of direction and precision after demagnetization. The precision at sites 10 and 38 increases by eightfold and fivefold respectively during cleaning.

A fold test applied to site mean directions from bands 1, 2, 4 and 5 is significant at the 95% level (but note that when this test is performed on band mean directions it appears to be non-significant, since the effect of folding is largely obscured by the band-mean calculation). The presence of pre-deformation tilting caused by basin-sedimentation would be eliminated by tilt correction only if the basin and the folding had the same horizontal axial trend. Evidence from the interbedded sediments shows that the basin deepened to the North and West during the period of ignimbrite eruption.

The procedure of applying a single tilt-correction, ignoring these early gentle warpings, introduces errors of no more than 10° in final directional estimation at individual sites, and these errors are not likely to be highly systematic. Therefore this simplified approach is adequate.

Fold tests can also be applied to each band individually and produce positive results for bands 2, 4 and 5. Poor precision and small dip variation of the bands precludes the application of decisive fold tests for bands 1 and 3 (Table 3.8). Because band 3 is bounded above and below by bands carrying a primary remanence it is difficult to envisage a secondary magnetization process restricted to band 3 alone. Therefore it is argued that the remanence found in band 3 is primary (or at least older than band 4 and the major folding) and hence band 3 records an instantaneous anomalous local geomagnetic field.

It is not possible to define the time interval between successive ignimbrites. The directions from bands 1, 2, 4 and 5 all fall within the S.E. quadrant, the inclination is downward varying from shallow to moderately steep (Table 3.8). Band 3, although fulfilling all the same stability criteria as the other bands and not showing any marked difference in intensity, gives a downward direction in the N.W. quadrant. The difference between bands 3 and 4 disagrees with the result of DEUTCH and SOMAYAJULU (1970). From these results it would seem that their statistical test actually applied to two units of band 4.

After a.f. cleaning at the chosen field, the range of intensities was markedly reduced 1.6×10^{-6}G to 0.9×10^{-6}G - but there is still no systematic variation between bands.

3.5.4. Discussion

Apart from discrepancies arising from possible correlation errors, the results of DEUTSCH and SOMAYAJULU (1970) are statistically identical with these in all major aspects. The directions estimated for each band agree, notably band 4 where this study gives $D = 137^{\circ}$, $I = +24^{\circ}$, $k = 45.0$; DEUTSCH and SOMAYAJULU have $D = 135^{\circ}$, $I = +22^{\circ}$, $k = 45.0$.

Since band 3 is anomalous it is not included in any overall analysis. Giving unit weight to each site yields a final result of D = 131°, I =+27°, k = 6 which is statistically indistinguishable from that quoted by DEUTSCH and SOMAYAJULU(1970), namely D = 135°, I = +36°, k = 12. Because of the unequal distribution of sites over the five bands sampled, it may be more correct to assign unit weight to each band. This analysis gives a final result D = 133°, I =+30°, k = 19 which corresponds to a pole at Long = 36°E, Lat = 10°S; DEUTSCH andSOMAYAJULU (1970) calculated their final result as D = 134°, I = +32°, k = 23, on the premise that they had sampled four bands; recalculating on the basis of three bands which it appears they actually sampled gives D = 135°, I = +37°, k = 25. This revision is minor however, and the basic agreement between the two studies remains. Hence the reported palaeomagnetic direction in the Mweelrea ignimbrites is completely verified.

3.6 Derry Bay Ignimbrite, Kilbride Peninsula

GARDINER and REYNOLDS (1912) have described a felsite on Kilbride Peninsula which they regarded as of intrusive origin: this is debateable. The base of the felsite where it is seen in contact with the underlying spilites is more indicative of extrusive origin. In thin section the felsite typically shows corroded quartz crystals, weathered felspars, with subsidiary magnetite and chlorite, texturally, it is coarse grained, and holocrystalline.

The basal Silurian sandstone and keratophyre of Upper Llandovery age (McKERROW and CAMPBELL 1960) give a minimum age limit for the felsite, while the Arenig bedded cherts of Knock Kilbride (DEWEY, RICKARDS, and SKEVINGTON 1970) provide a maximum age limit. Time must be allowed, however, for an intervening episode of deformation hence yielding Llanvirn/Llandeilo as the probable age of 'intrusion'. This is in close agreement with the time of formation of the Mweelrea ignimbrites further West in the Mayo Trough (WILLIAMS 1972).

Folding of the felsite is very simple, merely gentle tilting to the North, but faulting is much more complex. The Derry Bay, and Doon Rock faults both have long and complicated histories (DEWEY, MOORBATH, and McKERROW 1970, and Figure 3.1). It has also been suggested (McMANUS 1967) that the eastern margin of the felsite is bounded by a NW-SE trending wrench fault (the Lettereeneen Fault zone). All palaeomagnetic sampling was by sun and/or magnetic compass. Six sites were collected from the margins of the main felsite mass, one from a fault-sliver on Red Island, and one from a small outlier on the Kilbride peninsula.

Standard a.f. demagnetization techniques were applied to the collection; Figure 3.5 summarises the details of the cleaning. Notable features are; (a) movement of the remanence vector away from the present geomagnetic field, and (b) the strong similarity between the intensity decay curves of all the samples.

After cleaning the six sites have significantly grouped remanence (Table 3.9). These can be split into two groups; (a) steep inclination and easterly declination, and (b) shallow inclination and Southerly declination (Table 3.10). A good first approximation to the dip of the felsite is given by the contact between the spilites and the main felsite mass, which is 20° to the north. Applying this tilt correction to the two groups, (a) direction gives a mean of $D = 192^{\circ}$, $I = +28^{\circ}$, $k = 7.8$, based on four sites, with a corresponding virtual geomagnetic pole at Lat = 21°S, Long = 338°E ($d\psi = 21^{\circ}$, $d\chi = 38^{\circ}$). This is similar, though slightly different in declination, to other Ordovician studies from the British Isles.

It does not agree with the result from the Mweelrea ignimbrites (Chapter 3.5), hence, either the felsite is stratigraphically below the Salrock fault, or if above the fault, then in this part of the Mayo Trough the

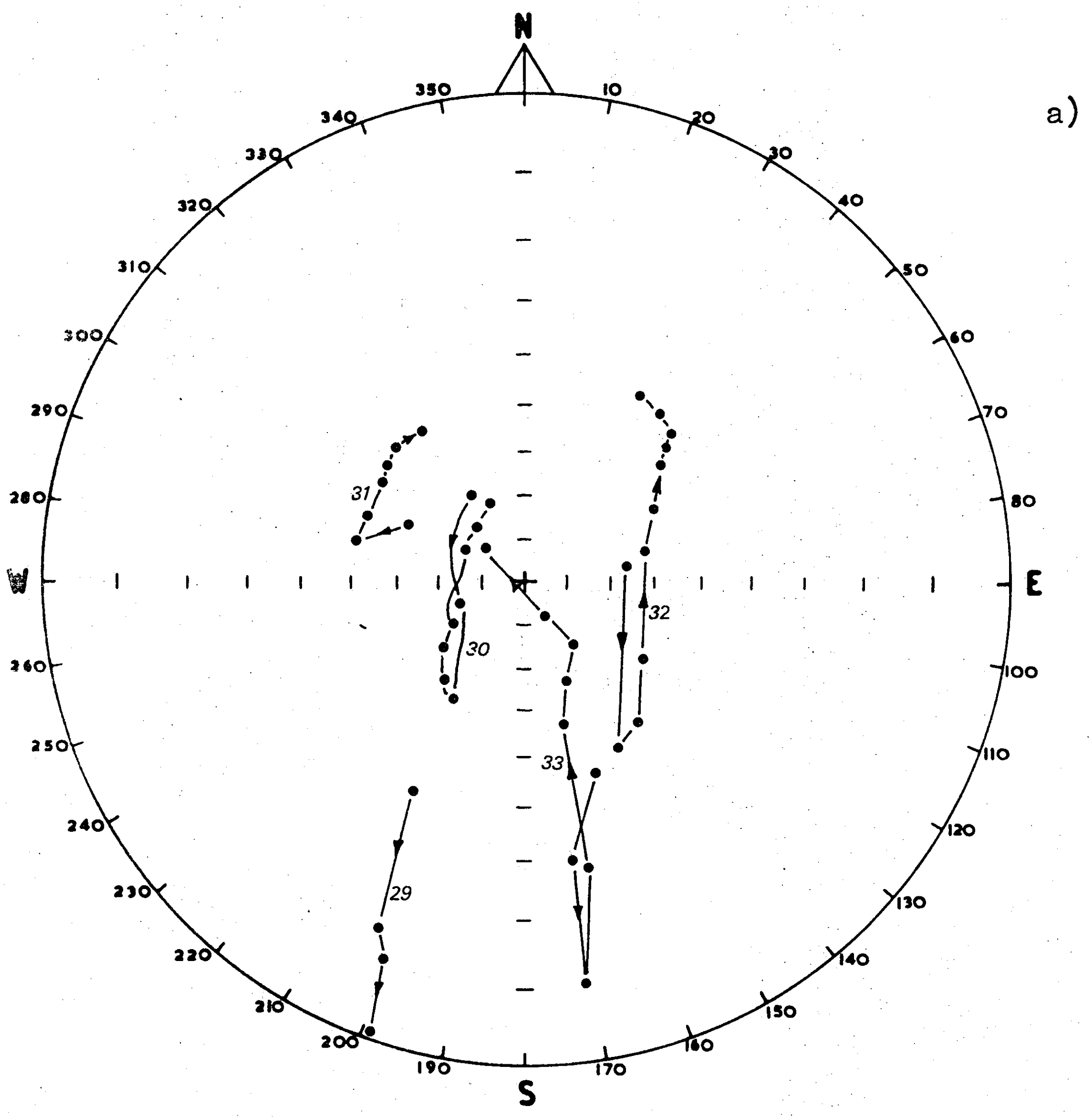
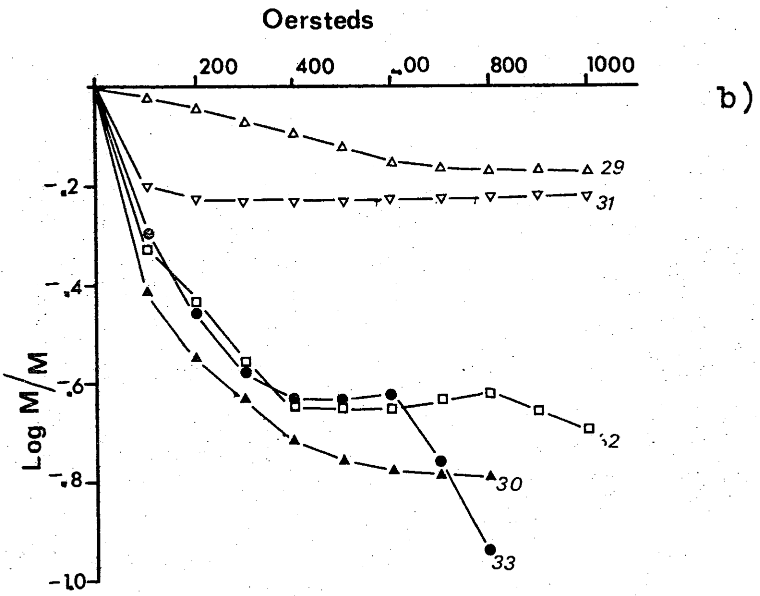


Figure 3.5. Variation of remanence direction (a), intensity (b), and Stability Index (c) upon a.f. demagnetization.



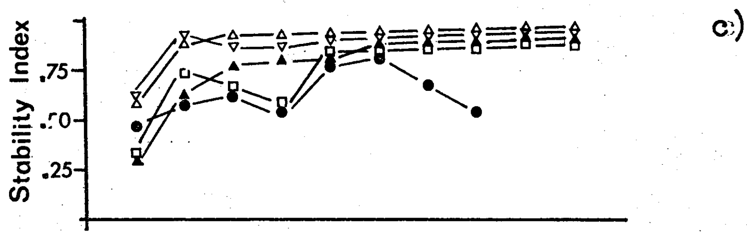


Figure 3.5. b) and c).

fault plane has become steep and the throw reversed. In the West of the Mayo Trough the Salrock Fault is a low angled thrust.

The in situ mean of group (b) based on twelve samples at D = 59°, I = +84°, k = 6.6, cannot be interpreted in terms of any known Palaeozoic or younger local geomagnetic field. Applying the same tilt correction as for group (a), does not produce an interpretable result. The only geological possibility is inaccurate tilt correction caused by proximity to the Derry Bay Fault, but applying any locally acceptable tilt correction yields only anomalous remanence directions. If both directions are primary then this implies two or more flows within the felsite. Possible geomagnetic explanations of the anomalous directions are de~~f~~ferred to Chapter 5.

3.7 The Glensaul Felsite

In the valley of the Glensaul river outcrops another of th felsite bodies which appear to mark the eastern margin of the South Mayo Trough. As with the Derry Bay, and the Tourmakeady Felsites (GARDINER and REYNOLDS 1908, 1912), age relationships, and mode of formation ~~is~~ are debateable. The only published account of the Glensaul body is by GARDINER and REYNOLDS (1910), although DEWEY and McKERROW (unpublished map), and WILSON (Ph.D. Leeds) have remapped the area. Outcrops of the Glensaul felsite are a series of fault-bound blocks e.g. the Tonaglana and the Greenaun masses. Many of the faults run NNW-SSE parallel to the trend of the Maam flexures (STANTON 1960), and the Lettereeneen fault zone (McMANUS 1967). Movement on these faults is mainly of late Silurian age.

The beds dip simply to the North; the amount of tilt is variable due to the complex faulting. Cherts which outcrop directly below the Greenaun mass have a mid-Arenig age, similar to the cherts underlying the Derry Bay felsite and interbedded with the Lough Nafooey spilites (DEWEY, RICHARDS, and SKEVINGTON 1970). Graptolites from above the Greenaun mass indicate an Upper Arenig age. GARDINER and REYNOLDS (1910) suggested the felsite was intruded into its present position; re-mapping the same area G.H.WILSON (personal communication 1973) has concluded an extrusive origin.

Seven sites were collected for paleomagnetic analysis. All the samples were collected by block sampling; and orientation was by magnetic compass.

Only four sites (60, 62, 63, 64) have significantly grouped total NRM (Table 3.11). Giving unit weight to each specimen the <u>in situ</u> site mean remanence is D = 295° I = +65°, k = 5.3. Simple a)

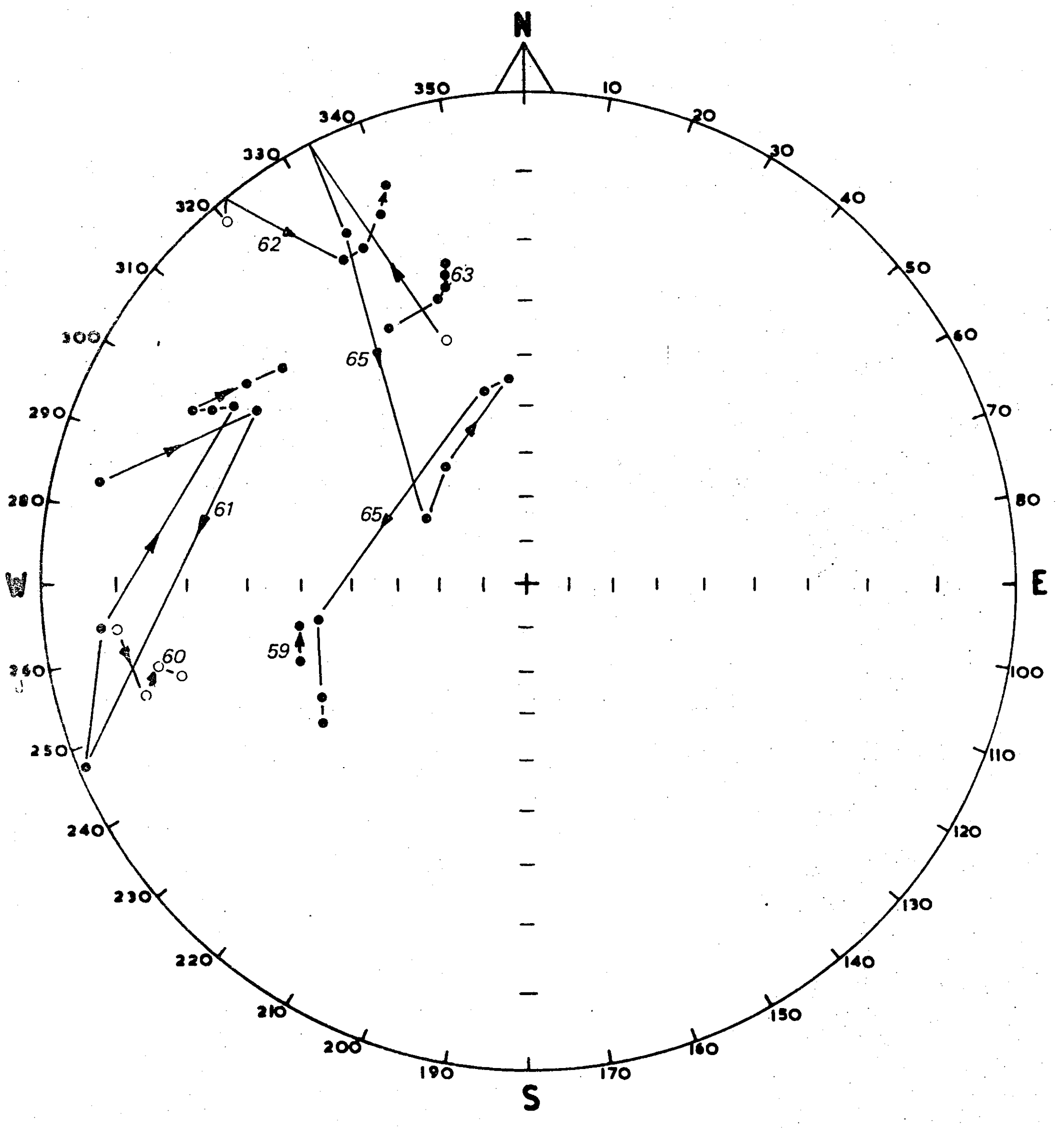
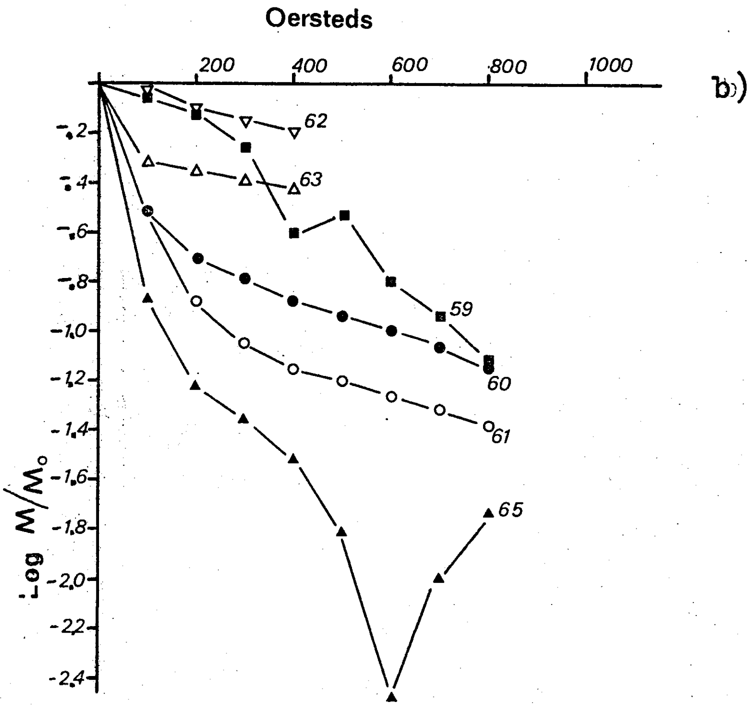


Figure 3.6. Variation of remanence direction (a), intensity (b) and Stability Index (c) upon a.f. demagnetization.



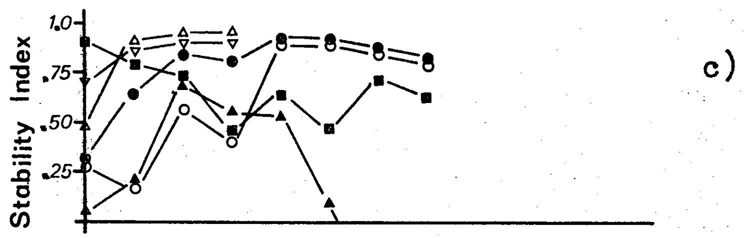


Figure 3.6. b) and c).

northerly tilt correction produces a slight numerical decrease of precision and moves the mean direction to $D = 317^{\circ}$, $I = +18^{\circ}$ $k = 4.3$. The a.f. demagnetization characteristics are plotted in Figure 3.6.

After cleaning all sites are statistically significant (Table 3.11). The _in situ_ mean remanence direction for the seven sites is $D = 309^{\circ}$, $I = +65^{\circ}$, $k = 2.6$ (Table 3.12). The site mean directions, fall into two groups which correspond to different levels in the felsite. Sites 59, 64, and 65 (Group 1) are from near the base of the felsite, while sites 60, 61, 62, and 63 (Group 2) are from near the top of the felsite.

Tilt correction of the group one results gives a mean direction of $D = 209^{\circ}$, $I = +43^{\circ}$, $k = 4.0$ ($n = 16$ specimens), which corresponds to a virtual geomagnetic pole at Lat = 8°S, Long = 323°E ($d\psi = 16^{\circ}$, $d\chi = 26^{\circ}$); a recognizably Ordovician remanence direction (BRIDEN, MORRIS and PIPER 1973). Once again the group two results present the problem of an anomalous remanence direction, at this point the data is given but interpretation is deferred to Chapter 5. The _in situ_ mean is $D = 353^{\circ}$, $I = +75^{\circ}$, $k = 6.4$, based on twenty-one samples, tilt correction gives a mean at $D = 335^{\circ}$, $I = +20^{\circ}$ $k = 6.8$. Intensity at these sites is not significantly different to that of the group one sites. If both groups record a primary field direction, then this implies more than one period of magnetization, i.e. more than one lava flow, or localised remagnetization.

3.8 The Upper Llandovery Keratophyre-Lough Nafooey

The basal Silurian of the Mayo Trough has been described by GARDINER and REYNOLDS (1912, 1914), McKERROW and CAMPBELL (1960), and PIPER (1970). This volcanic horizon was originally mapped as an intrusive, but the presence of large lava clots in the overyling sediments has established its extrusive origin. Total thickness varies from zero to 115m. Many outcrops have a spheroidal appearance, which McKERROW and CAMPBELL (1960) interpeted as lava pillows. PIPER (1972) however, has argued that this is purely a weathering effect, since internal structure bears no resemblance to external appearance. For primary structures, magnetic intensity should vary, but NRM direction should not, whereas secondary alteration would create marked intensity and direction variations. There is also some disagreement on the overall structure of the Silurian, PIPER (1972) has suggested a repitition of strata due to block faulting, while McKERROW and CAMPBELL (1960) interpret the structure as a series of open E-W trending anticlines and synclines.

Both hand and field-drilled samples were collected for palaeomagnetic analysis. The total NRM site mean statistics are given in Table 3.13 . Only one site has non-significantly grouped remanence. The in situ mean direction of the ten sites is $D = 329^{\circ}$, $I = +80^{\circ}$, $k = 10.1$ close to the present geomagnetic field; tilt correction produces a non-significantly grouped mean. Progressive a.f. demagnetization variations are shown in Figure 3.7.

The a.f. cleaned site mean statistics are given in Table 3.14. The site means can be separated into three groups: (1) normal, sites 36, 38, 40 and 44 (2) reversed, sites 34, 42, and 43: and (3) intermediate, sites 35, 39. There are two interrelated indications of primary remanence. Tilt correction within both the normal and the reversed groups give a fold test of remanence, significant at the 95% level (McELHINNY 1964). The in situ means of the normal and reversed groups are 40° apart, while the tilt corrected means

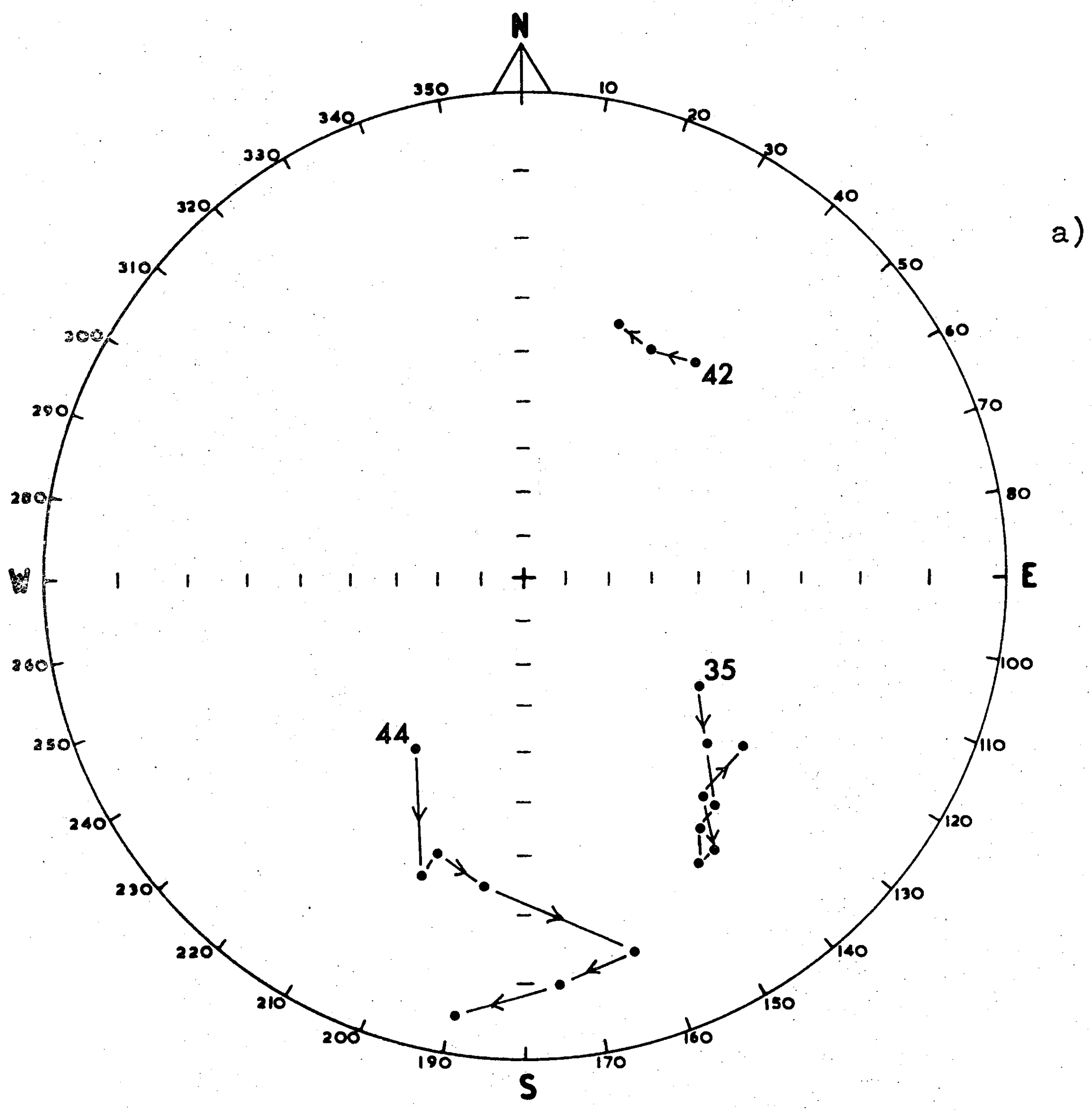
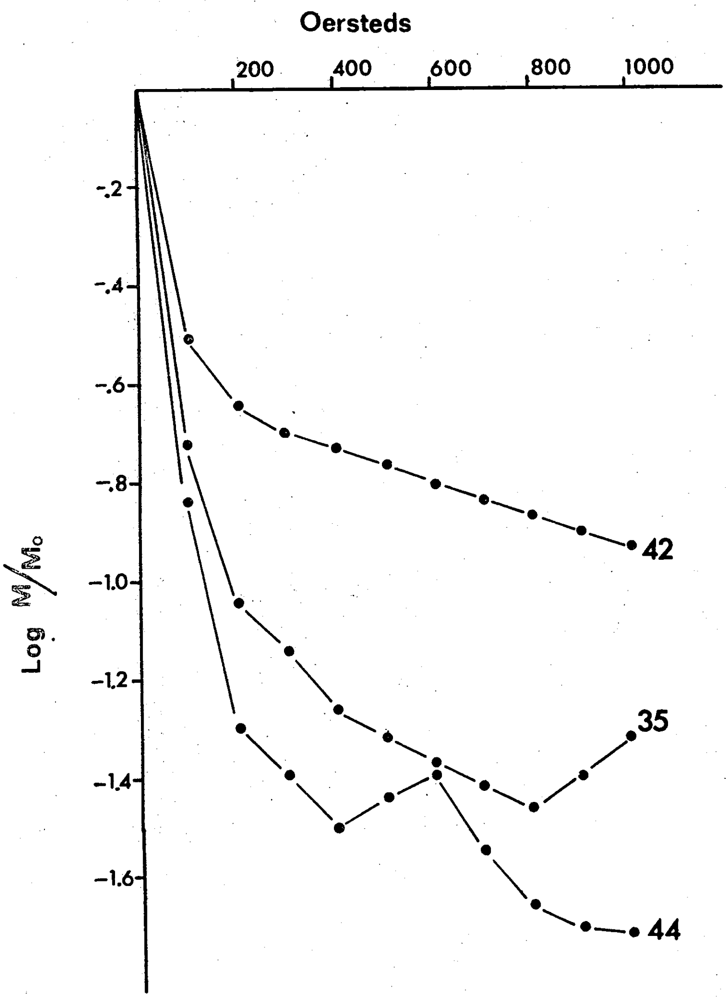
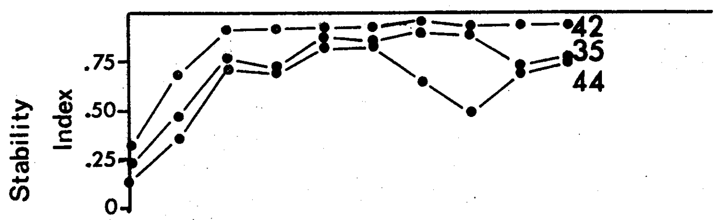


Figure 3.7. Variation of remanence direction (a), intensity (b), and Stability Index (c) upon a.f. demagnetization. Sample 42 - normal, sample 44 - reversed, and sample 35 - intermediate.



b)



c)

Figure 3.7. b) and c)

are 150° apart. The tilt corrected mean direction irrespective of polarity is D = 35°, I = -5°, which corresponds to a paleomagnetic pole at Lat 27°N, Long = 130°E, ($d\psi$ = 15°, $d\chi$ = 30°). This is similar to the result from the Tortworth traps also of Upper Llandovery age. (MORRIS, BRIDEN, PIPER, and SALLOMY 1973), which also record a similar polarity reversal.

The two intermediate group sites, have an in situ mean direction of D = 102°, I = 86°, k = 5.0; tilt correction gives a mean at D = 145°, I = 25°, k = 5.3, both based on eleven samples (Table 3.15). Interpretation of this result is deferred to Chapter 5.

Since lavas necessarily cool in a geologically short period of time, they must record the instantaneous local geomagnetic field. Hence a correlative of this interpretation of the data is that the keratophyre is formed of at least three (or probably more) lava flows.

3.9 Salrock Formation sediments and associated Intrusives

3.9.1 Geology and sampling

The youngest Lower Paleozoic of the Mayo Trough are a 800m. thick sequence of siltstones, sandstones and shales, which outcrop on the south side of Killary Harbour (Figure 3.1). LAIRD and McKERROW (1970) considered these beds (Salrock Formation) to be Wenlock in age as they directly overlie middle-Wenlock sediments (Upper Owenduff Formation). Intruded into the Upper Owenduff are two granodiorite sills, while intruded into the Salrock Formation are three andesite sills and two lamprophyre sills. The contact between the andesite and the adjacent sediments suggests that they were intruded prior to complete lithification (LAIRD 1969). On this assumption, and since the sediments were deformed near the end of the Silurian, the age of the intrusives is confined to the interval Upper Wenlock-end Silurian.

The top of the sequence is not seen, being hidden under Arenig rocks, which have been thrust southward on the Salrock Fault. Within the sections sampled in the Salrock Formation there is no large scale folding, all the sites have varied steep northerly dips. The amount of internal deformation increases towards the thrust plane, near which intense cleavage and complex minor folding precluded any palaeomagnetic sampling. In the sediments outcrop was very good; it was possible to sample two measured sections. Sites were collected at approximately 15m. intervals, in the hope of obtaining some information on Silurian short period geomagnetic variations.

3.9.2. Salrock Formation sediments-NRM and site mean analysis

Fifty-one sites have been collected from two measured sections in the Salrock Formation, which are 2km. apart. Only four sites have non-significantly grouped total remanence (Tables 3.16, 3.17). As thermal demagnetization was not available, attempts were made to clean the sediments using a.f. demagnetization, but in the main this produced only small changes of intensity and direction. Both red and green beds carry similar remanence directions. The a.f. demagnetization characteristics of the green beds eliminated members of the ilmenite-hematite series as possible remanence carriers suggestive of primary remanence. After cleaning the direction remained within the group of observations in the red beds (Figure 3.8).

The tilt corrected mean remanence directions of the two sections are: SAL 1, $D = 49^{\circ}$, $I = +1^{\circ}$, ($N = 28$ sites, $k = 7.8$) and SAL 2, $D = 40^{\circ}$, $I = +1^{\circ}$ ($N = 19$ sites, $k = 9.4$). Combining these two results, and giving unit weight to each site yields a mean of $D = 45^{\circ}$, $I = +1^{\circ}$ ($k = 8.4$) corresponding to a palaeomagnetic pole at Lat = 26°N, Long = 119°E ($d\psi = 4^{\circ}$, $d\chi = 8^{\circ}$).

The close comparison of declination and

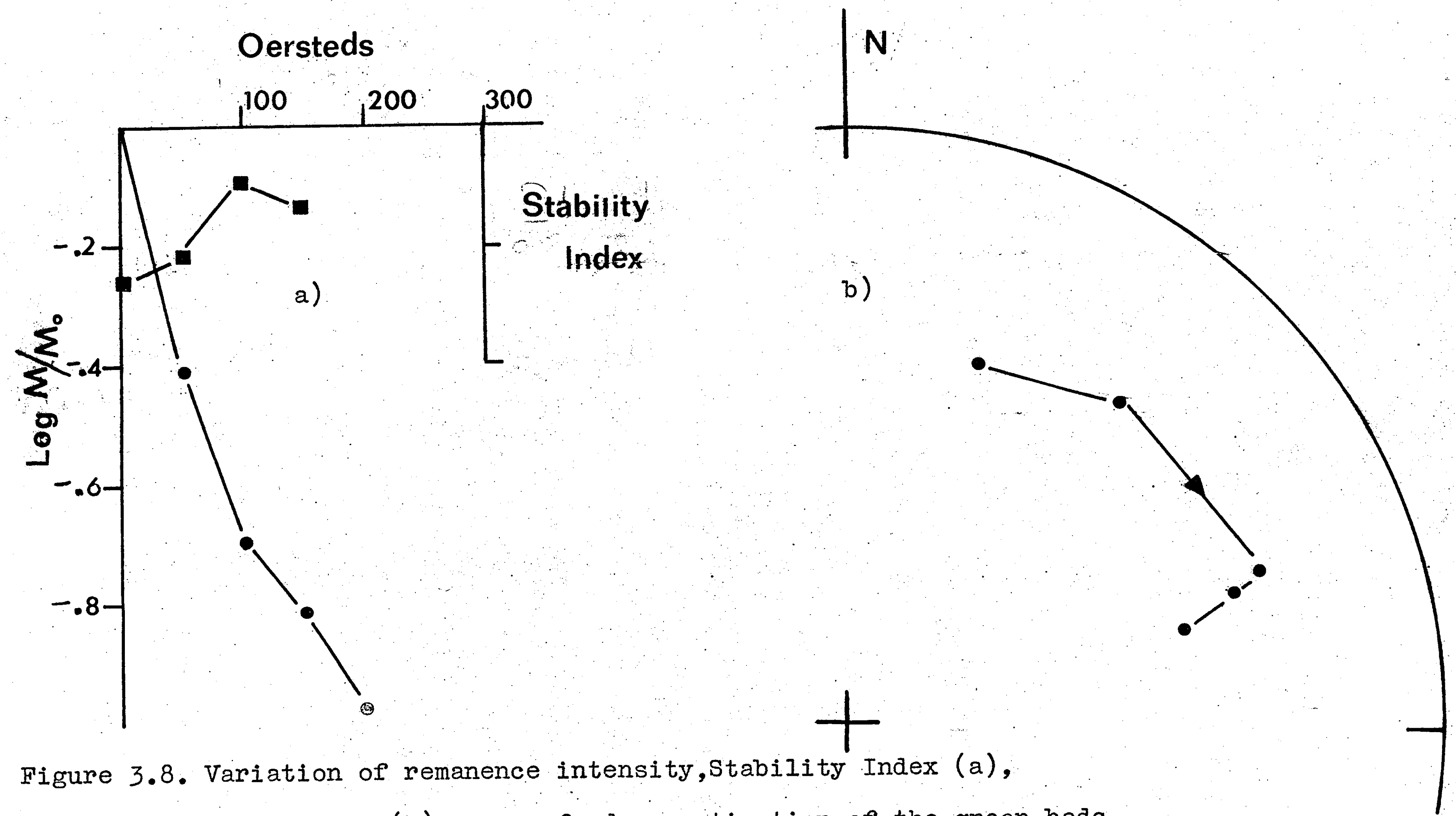


Figure 3.8. Variation of remanence intensity, Stability Index (a), and remanence direction (b) upon a.f. demagnetization of the green beds.

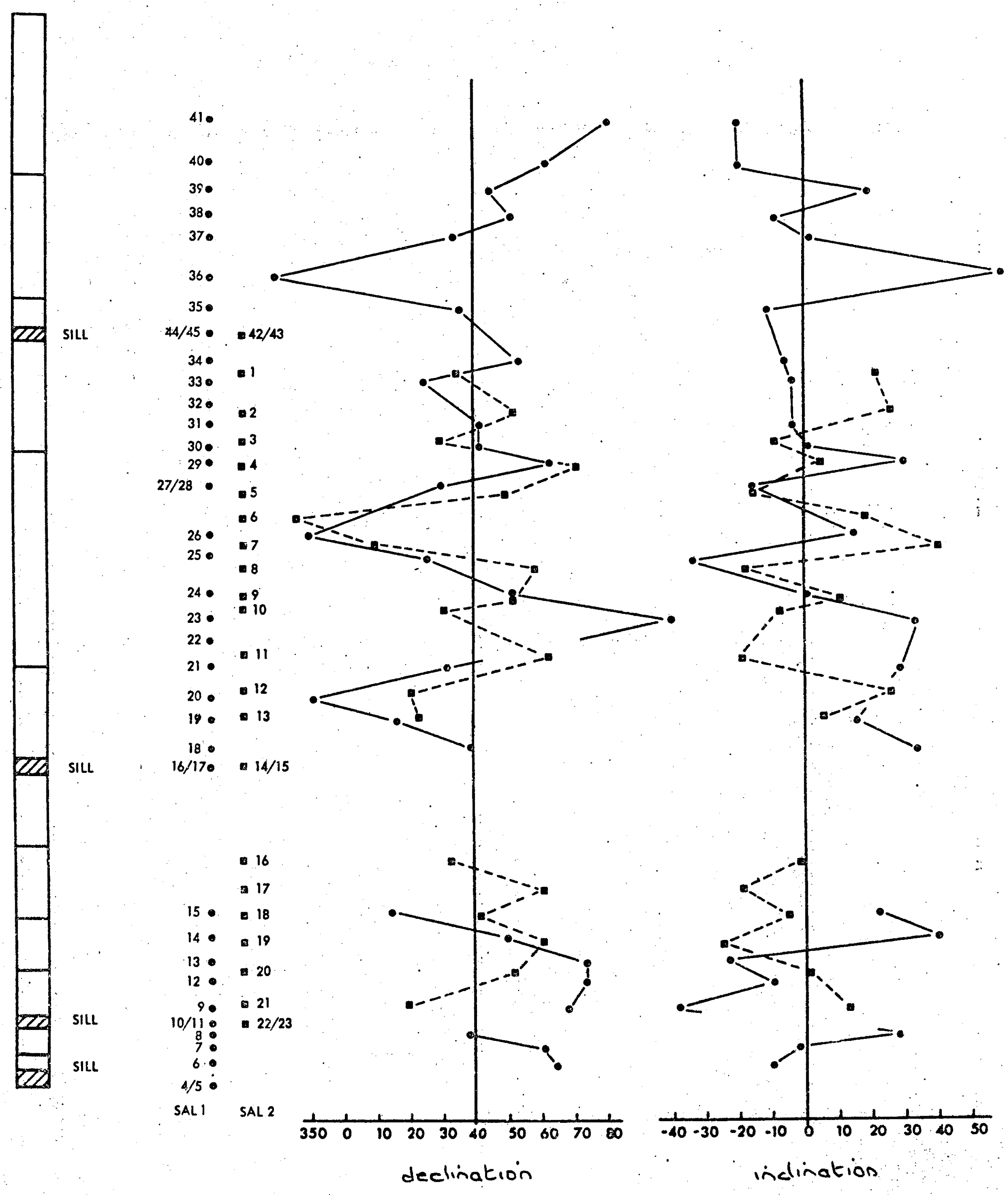


Figure 3.9. Comparison of remanence directions found in Sections SAL 1 and SAL 2.Sedimentary log by Laird(1969).

1cm= 100m.

inclination relative to position in the sedimentary pile between the upper part of the two sections is very good (Figure 3.9). Although the age of remanence relative to time of deposition is uncertain, it must either date from the actual time of deposition (DRM) or from some specific point during the lithification process (CRM). For the red sediments, the acid leaching tests of COLLINSON (1968), and PARK (1970) would clarify whether the remanence carrier is in specular or colloidal hematite. It has already been shown that the remanence carrier in the green beds, is some member of the magnetite-ulvöspinel séries. In either case the remanence is essentially primary, and is of upper Silurian age; it is difficult to imagine any secondary process that can selectively remagnetize a particular horizon over a distance of some two kilometres. Detailed correlation between the two sections is dependant upon local rates of sedimentation, hence curve amplitude and not curve shape, is the basic criterion for cross-correlation.

In the lower part of Figure 3.9 there is an obvious discrepancy between the results from the two sections, the curves appear to be out of phase by approximately 65m. On each traverse an andesite sill is used as the basal reference level. (SAL 1; sites 4/5, and SAL 2; sites 22/23) on the assumption that the sill maintains the same stratigraphic horizon from Section SAL 1 to Section SAL 2. On SAL 1 McKERROW and CAMPBELL (1960) map two andesitic sills at the base of the Salrock Formation, while on SAL 2 they show only one such sill; they regard the upper of the two sills of SAL 1 as continuous across to SAL 2. If this correlation is incorrect and in actual fact the basal sill of SAL 2 is the lower of the two sills of SAL 1, this would bring sites 4/5, SAL 1 and sites 22/23, SAL2 on the same level. Applying this amendment to Figure 3.9 brings the curves for the lower part of the succession into much closer agreement. It also brings site 15, SAL 1 and Site 16, SAL 2, to the same stratigraphic level, at this horizon the sediment changes colour from red to green. This correlation also creates a problem; if the lower part of the sequence of SAL 2 must be displaced downwards by some 65m., it follows that the upper part of the sequence should also be displaced by a similar amount. However, it has already been shown that the upper parts of SAL 1 and SAL 2 are in good agreement. Hence this incompatibility can be resolved in two ways, both of which require a reduction of the sediment thickness between sites 14/15 and 16 of SAL 2 compared with the interval between sites 16/17 and 15 of SAL 1.

Either a normal fault or a reduced sedimentation rate would produce the same required effect. There is no evidence for a fault. Using the map of McKERROW and CAMPBELL (1960), and now knowing that the intrusives are confined to a particular bedding plane, the second proposal can be tested. The thickness of the sediment between the lamprophyre and the lowest andesite sill on SAL 1 is 75m. greater than it is on SAL 2. Considering the many inaccuracies involved, it would seem that the paleomagnetic inferences are well substantiated.

A plot of all tilt corrected total NRM site mean directions has been contoured using the technique of KALSBEEK (1963, referred to by RAGAN 1968). The distribution of site means is oval and unimodal (Figure 3.10). Other significant properties of this collection are; (a) at each site care was taken to restrict sampling to a particular sedimentary horizon, (b) the planar extension of the site-mean distribution is along the paleo-meridian, (c) declination and inclination appear to vary antipathetically, and (d) the mean magnetic inclination for the collection is $+1^{\circ}$, implying an equatorial location at the time of sedimentation.

The overall mean of the Salrock Formation using FISHER's analysis falls on the saddle between two

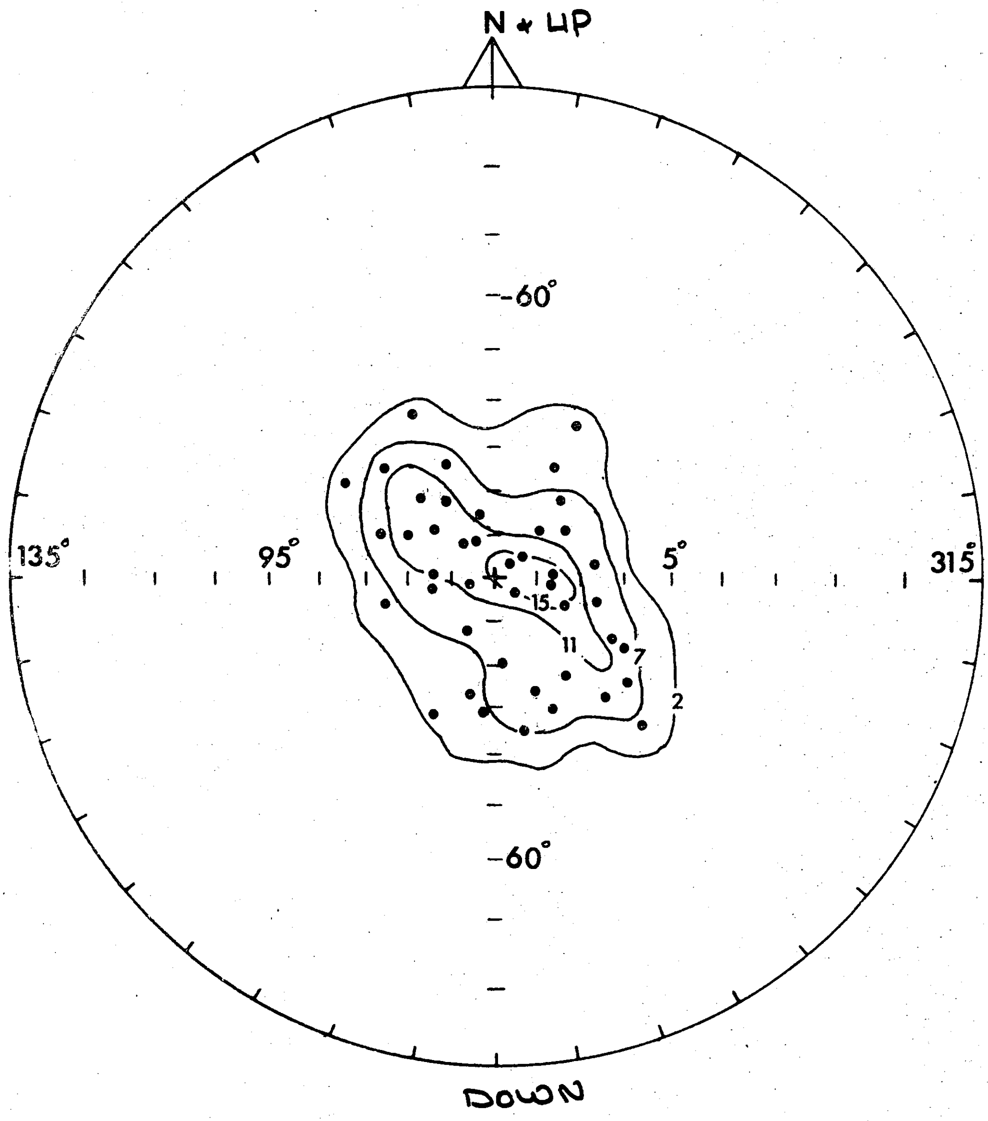


Figure 3.10. Contoured equal-area projection of all significant tilt corrected site mean directions.

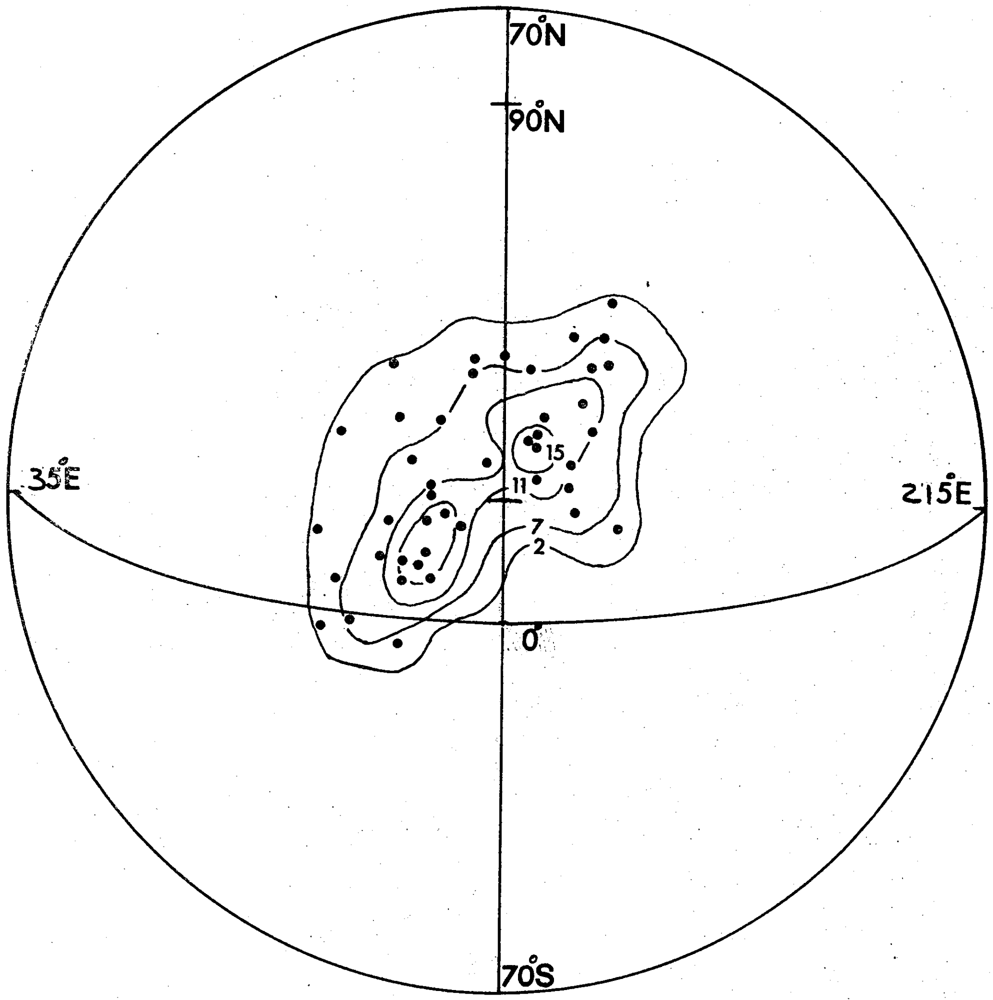


Figure 3.11. Contoured equal-area projection of all significant tilt corrected site mean virtual geomagnetic poles.

maxima. As remagnetization is not applicable, a bimodal polar plot (Figure 3.11) of primary magnetization implies two distinct periods of remanence. The two maxima correspond approximately to known Siluro-Devonian pole positions (BRIDEN, MORRIS and PIPER 1973). The two directions are not sequential in Figure 3.9 but intermixed, this must indicate two significantly different remanence modes: possibly DRM and CRM. Detailed grain size analysis, acid leaching stability tests, and rock magnetic analysis are necessary to validify the separation of these results into two groups. If this interpretation is correct, it suggests that the Salrock Formation carries two primary remanence directions and that Figure 3.9 is a plot not only of Silurian secular variation, but also of some as yet unknown primary sedimentary parameter.

3.9.3. Intrusives and baked contacts

Sampling of the Intrusives was by field drilling and block sampling. In the calculation of site mean statistics unit weight was given to each specimen. In all twenty sites were occupied, associated contact tests were collected for most of the intrusives. Each rock type is dealt with separately, and this is followed by an overall interpretation of the results.

3.9.4. Microgranodiorites

In this group there are nine sites with no contact tests, only two have non-significantly grouped total NRM. The in situ mean direction of the seven significant sites is D = 298°, I = +85°, k = 6.5. There is no geological evidence indicating whether intrusion was before or after tilting of the sediments, also there are no paleomagnetic field criteria to establish age of remanence A.f. stepwise demagnetization produced regular intensity decay, with little or no direction change. The optimum field for cleaning most sites was 300 Oe. After cleaning all the sites had significantly grouped remanence vectors (Table 3.20). The in situ mean direction for the nine sites is D = 263°, I = +53°, k = 10.6. The application of a northerly tilt correction produces only a slight increase of overall precision, but moves the site mean direction to D = ~~290~~ 318°, I = +~~46~~ 44°. (Table 3.21).

3.9.5. Andesites

All five sites which have igneous contact tests, are from the two sections sampled in the Salrock Formation. Only site 23 did not have significantly grouped total NRM remanence. In the baked sediments every site was significantly grouped. (Table 3.19).

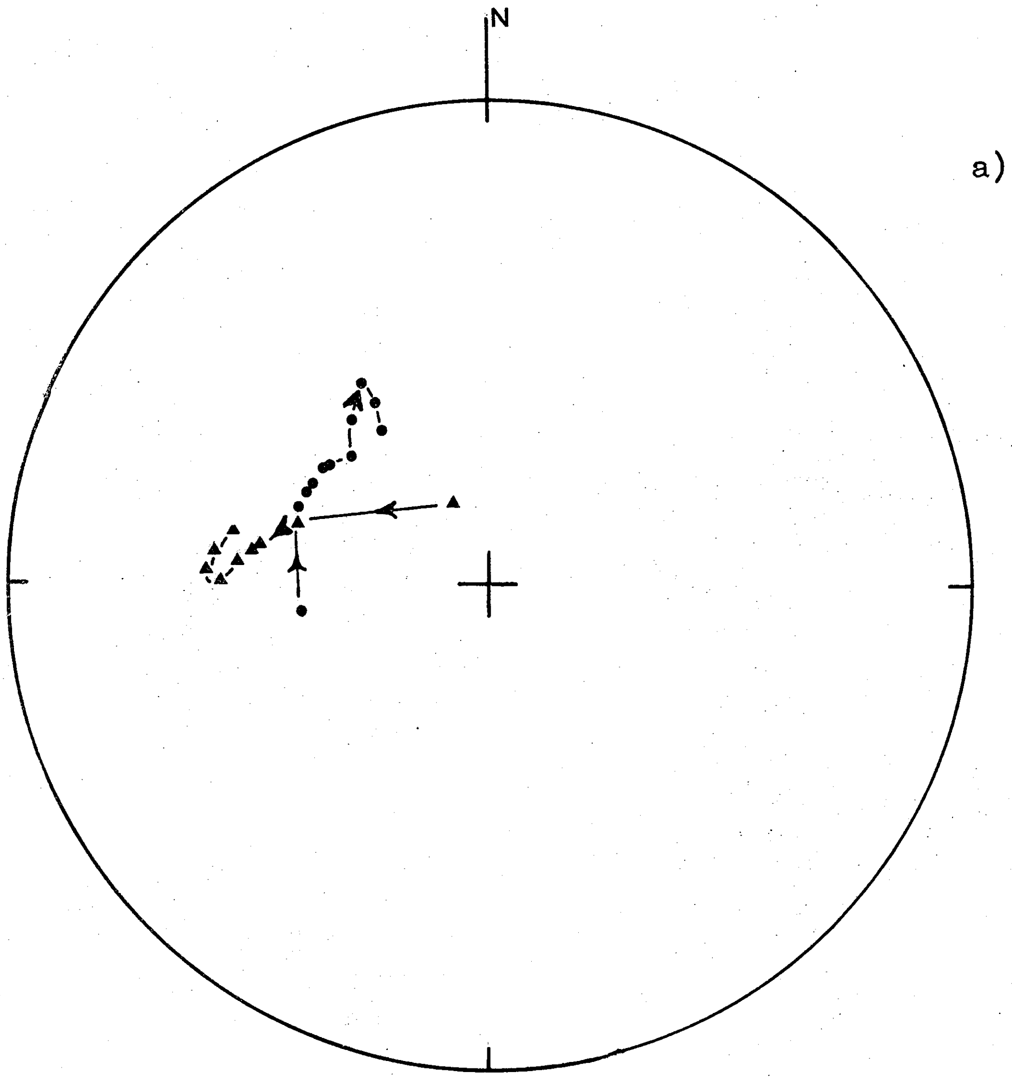
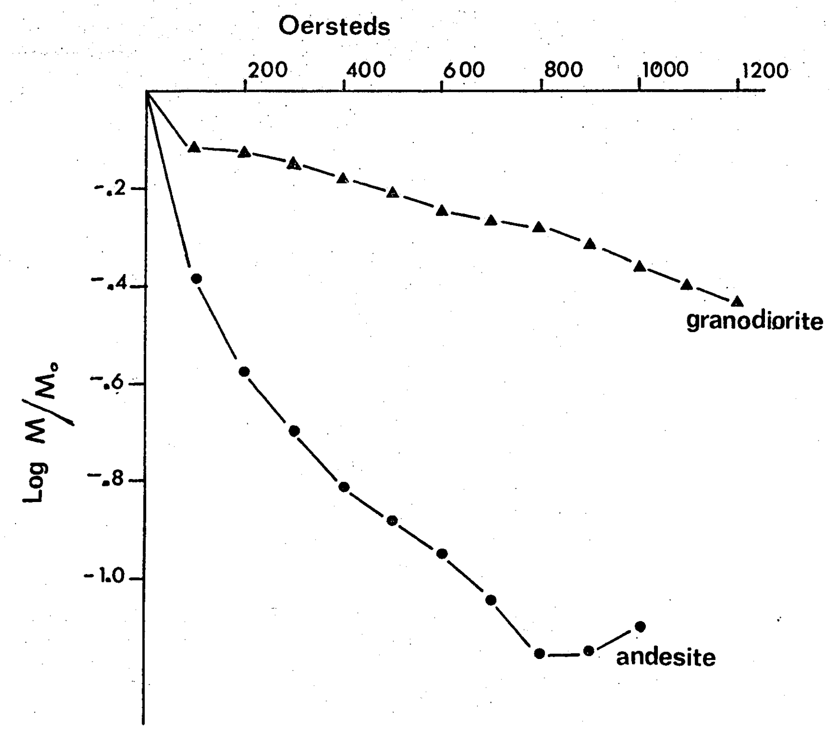
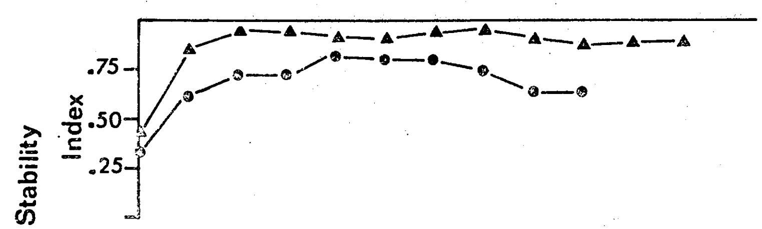


Figure 3.12. Variation of a) remanence direction, b) intensity, and c) Stability Index upon a.f. demagnetization. Triangles - granodiorite, dots - andesite.



b)



c)

Figure 3 .12.

The *in situ* mean direction of the significant sites is D = 252°, I = +48°, (k = 5.2). Tilt correction reduces the overall precision to 4.8 and moves the mean direction to D = 339°, I = +48°.

A.f. demagnetization characteristics are summarized in Figure 3.12. The cleaned directions for the dyke, the contact and the combined means are given in Table 3.20. Applying the tests of WATSON (1956 a) it can be shown that only at site 11 do the contact and intrusive have significantly different site mean directions at the 95% level. However, even though the contact samples of site 11 may not have been in the baked zone, but they were most definitely in the warmed zone (IRVING 1964); the difference in mean direction between the 'baked' contact and 'unbaked' sediments samples is much greater than that between the contact and the intrusive samples. The *in situ* mean direction of the andesites giving unit weight to each site is D = 252°, I = + 20° (k = 7.4) (Table 3.21). Applying a steep northerly tilt correction gives D = 290°, 1 = +46°.

3.9.6. Lamprophyres

There is only one lamprophyre sill intruded in the Salrock Formation, this was sampled on the two sections, in each case there is also an igneous contact test. Four other sites were sampled in the sill where it outcrops further to the west. Total NRM statistics are summarised in Table 3.19. The *in situ* mean NRM direction is D = 280°, I = +72°, (k = 9.5), tilt correction increases the overall mean to k = 11.3 and moves the mean direction to D = 344°, I = +25° (Table 3.21).

After a.f. cleaning all sites were significantly grouped, the contact zones do not significantly differ from their adjacent intrusives (WATSON 1956 a). The in situ mean is D = 240°, I = +38° (k = 13.6); tilt correction produces a mean of D = 299°, I = +45°, (k = 15.2) (Table 3.21).

3.9.7. Discussion

In the overall analysis contact and igneous samples are treated as one site (Table 3.22). The remanence in the intrusions is likely to be primary because the contact tests show almost anti-parallel magnetizations between the baked and the unbaked sediments. The three groups have statistically identical in situ remanence directions (Table 3.22); their combined in situ mean direction is D = 254°, I = +41°, (k = 8.0) corresponding to a paleomagnetic pole at Lat = 9°N, Long = 286°E. Tilt correction gives D = 306°, I = +45° (k = 9.7) corresponding virtual geomagnetic pole Lat = 42°N, Long = 248°E ($d\psi$ = 9°, $d\chi$ = 14°), (Table 3.23).

If these intrusives are all of a similar age, then they . necessarily bear the same relationship to the tilting of the sediments. The only geological evidence for pre-tilting intrusion is highly contorted sediments as a result of degassing when hot magma is intruded into wet sediment (Laird 1969). However, paleomagnetism tends to suggest the opposite conclusion; the in situ mean direction of the intrusives is 150° away from the tilt corrected sediment mean direction, while the tilt corrected mean direction for the intrusives is only 90° away. Assuming a fairly constant geomagnetic field direction over the period from sediment deposition to magma intrusion, a separation of 150° is more readily explained in terms of a field reversal, than 90° whose interpretation is problematical. Furthermore comparison of the intrusive mean directions with results of similar age from England (BRIDEN, MORRIS and PIPER 1973) suggests that the tilt corrected result must be regarded as anomalous, while the in situ mean is in close agreement.

Finally, if the sills were intruded at different times with respect to the tilting of the beds, then both the in situ and the tilt corrected mean results are valid.

3.10 The Knockaveen Group, Louisburgh

The northern margin of the Mayo Trough is marked by a major fault system which has been compared to the Highland Boundary Fault Zone (DEWEY 1969). Outcropping to the North of the fault are highly metamorphosed Dalradian sediments and volcanics, while to the South are folded, and metamorphosed Silurian sediments, the fault line is marked by serpentinite bodies. Thrust over this contact from the North is a series of unmetamorphosed Wenlock redbeds referred to the Knocknaveen Group (PHILLIPS, RICHARDS and DEWEY 1970). It has been suggested that the sediments, which range from arkoses to fine silstones, are in part lateral equivalents of the Salrock Formation (Section 3.9).

Folding is complex, occurring on two scales, fold tests of remanence are possible not only between sites over some 15 km., but also within site on the scale of a metre. The axes of the folds are mainly E-W with variable plunge, areas with plunges greater than 30^{o} were mostly avoided, since they require multi-stage tilt correction (BRIDEN and MORRIS 1973).

A provisional result based on thirteen sites is given in Table 3.23. Sites are not all from the same thrust slice. Site 2 was collected from a minor plunging fold, hence it was possible to correct samples for both bedding tilt and fold plunge. Overall grouping is poor, although some of this disrepancy may be due to the lack of cleaning, most is probably due to the complex tilt corrections involved. Many of the beds are overturned, so the assumption of purely cylindrical folding at this point cannot be strictly valid.

Progressive a.f. demagnetization was attempted on some specimens; as is common with red beds cleaning even up to 1800 Oe. (peak) produced little intensity or direction change. The only exceptions were two samples from Site 1, whose NRM site mean direction diverges from the mean of Sites 2 - 18. During progressive a.f. cleaning the direction of the Site 1 samples moves into the NW quadrant with negative inclination in closer agreement with the directions recorded at Sites 2 - 18. Attempts at chemical demagnetization of the samples produced negligible results, but then the samples were not treated over an extended period.

Tilt correction within Site 2 does not produce a large increase of precision, since the bedding strike and the remanence vector are almost parallel. The <u>in situ</u>

analysis of the thirteen Sites is D = 165°, I = -15°, k = 2.1, does not match with any British Paleozoic direction yet known. The tilt corrected result at D = 41°, I = -31°, k = 2.2 (paleomagnetic pole Lat = 11°N, Long = 130°E) compares closely with Siluro-Devonian results from Great Britain.

3.11 Summary and Conclusions

New data have been reported from the Lower Paleozoic of the South Mayo Trough. The anomalous result of DEUTSCH (1969) from the Mweelrea ignimbrites is completely verified. Studies from the basal Arenig pillow lavas yield consistent results; the Lough Nafooey spilites exhibit dual polarity with a paleomagnetic pole at Lat = 42°N, Long = 165°E ($d\psi = 9°$, $d\chi = 18°$, N = 15 sites) The South Connemara Series yield a pole at Lat = 42°N, Long = 164°E ($d\psi = 24°$, $d\chi = 47°$, N = 6 sites). Small collections were also reported from the Ordovician Derry Bay and Glensaul Felsites, both of which yielded two remanence directions, one comparable to that found in the Connemara Gabbros (Morris and Tanner in preparation), and another which is considered anomalous.

The basal Silurian Keratophyre of Upper Llandovery age, shows a polarity reversal similar to that in the contemporaneous Tortworth Traps. The Salrock Formation of Wenlock age carries two remanence directions related to some unknown sedimentary parameter; it is shown that a remanence direction log can be used for detailed stratigraphic correlations. Sills intruding the Salrock and the underlying Upper Owenduff Formations give an <u>in situ</u> paleomagnetic pole at Lat = 9°N, Long = 286°E ($d\psi = 9$, $d\chi = 15$, N = 20 sites). Finally, the Knockaveen Group, Louisburgh yields a paleomagnetic pole based on NRM results of Lat = 11°N, Long = 130°E ($d\psi = 23^{\circ}$, $d\chi = 43^{\circ}$, N = 13 sites), which is significantly different to all other Silurian results from the Mayo Trough.

Palaeomagnetic results from the Ordovician of Western Eire fall into three groups (Figure 3.13), (a) Connemara Gabbros (MORRIS and TANNER, in preparation) Derry Bay and Glensaul Felsites, (b) Lough Nafooey Spilites and the South Connemara Series, (c) the Mweelrea ignimbrites. The directional differences between these groups is mainly in declination, hence the disparities may be the result of local tectonic rotation. To discuss possible rotations it is necessary to establish some point of reference, with which to compare individual directions.

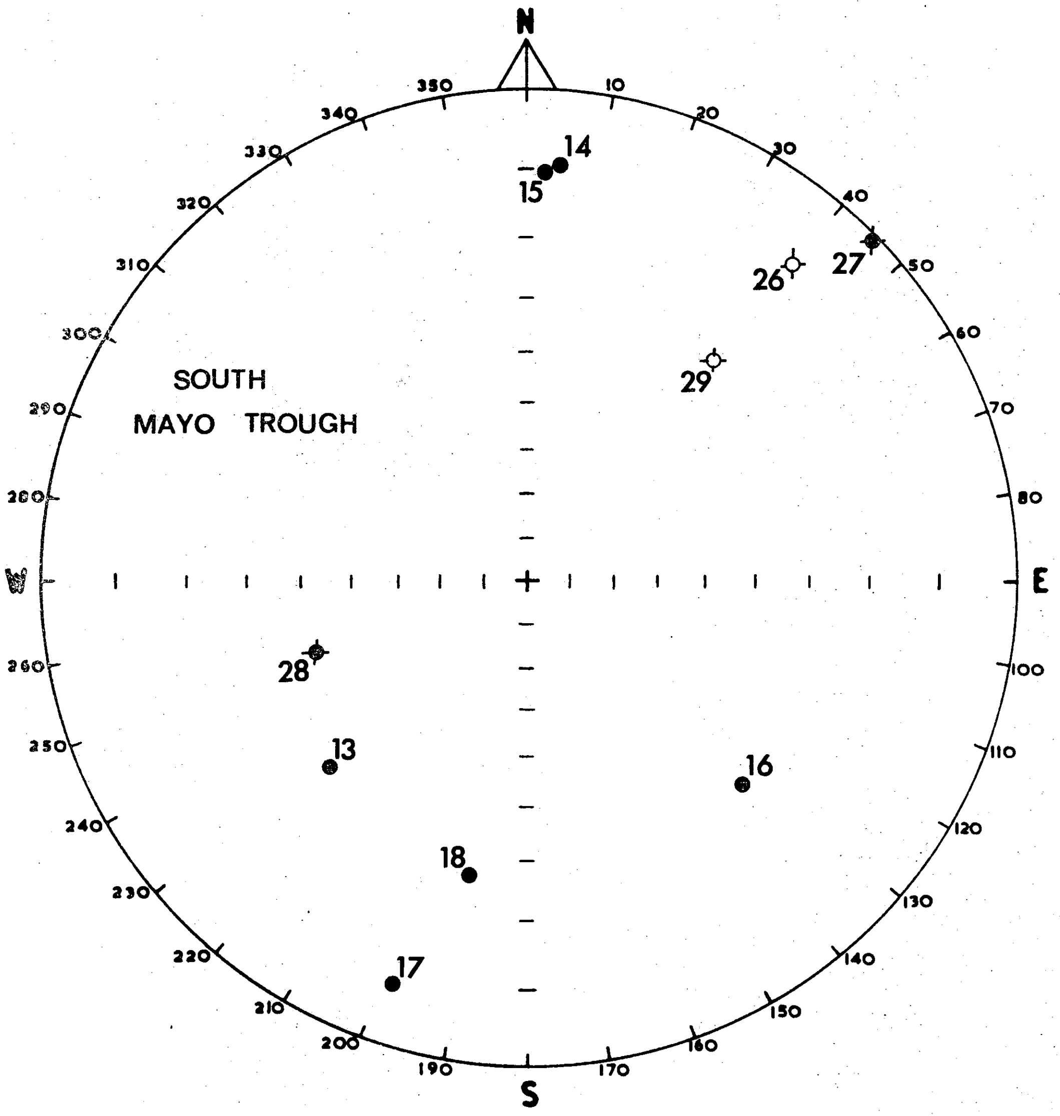


Fig ure 3.13. Remanence directions from the South Mayo Trough,numbers refer to Table 5.1.
Dots - Cambro-Ordovician,Barred dots - Siluro-Devonian.

Because of the consistency of results from the Eycott Group, the Builth Volcanic Series, and the Aberdeenshire Gabbros, the mean of these directions is taken as the best estimate of the ambient Ordovician geomagnetic field.

Comparing the results from Western Eire with this mean implies different rotations for the three groups. They are respectively: (a) a 40° clockwise rotation, (b) no rotation, (c) a 40° anti-clockwise rotation (Figure 5.6). It must be pointed out that all the Silurian studies from Mayo also appear to have suffered a 40° clockwise rotation (Figure 5.7). In general Caledonoid structures have a NE-SW trend, but in the Mayo Trough this has been swung through some 40° to become E-W. Hence, both palaeomagnetic and geologic evidence suggest a post-Silurian clockwise rotation of Western Eire.

The Mweelrea ignimbrites show a 40° anti-clockwise rotation; in Section 3.3 this was interpreted as due to rotation on the end-Silurian Salrock Thrust. It is envisaged that this thrust developed at the same time as the more regional rotation, i.e. the Mweelrea ignimbrites were on an allochthonous sheet which over-rode the Connemara block while it was being driven northward.

The Knocknaveen Group, Louisburgh and the spilites (Group b) are special cases. Unlike other Silurian results from Mayo the Knocknaveen Group yields a palaeomagnetic pole close to most other Siluro-Devonian results from Britain. This agreement is attributed to anti-clockwise rotation on the Emlagh Thrust (PHILLIPS, RICKARDS and DEWEY 1970) which has annulled the regional clockwise rotation. Like the Salrock thrust, the Emlagh thrust is of post-Silurian age and shows a southerly sense of movement.

The spilites do not appear to have been rotated; this can be interpreted in four ways. Firstly, the spilites could be younger than the rotation. Secondly, they may occur in special blocks which have not experienced rotation. Thirdly, tilt correction is either inaccurate, or inadequate for the structural complexities present. Finally, it is possible that the spilites have suffered some pre-end Silurian rotation of an exactly opposite amount. As there is plenty of evidence indicating an Ordovician age for the spilites the first suggestion is untenable. It has been found that the end-Silurian rotation is applicable from South Connemara to Clew Bay, hence it is difficult to visualize how certain blocks can remain completely unaffected. As mentioned previously (Sections 3.2, 3.3) the detailed internal structure of the spilites is unknown, and moreover may be complex.

If the spilites plunge at 30° to the East as suggested by G.H. WILSON (personal communication 1973), then correcting for the two components of tilt yields remanence directions which closely agree with the group (a) directions. Petrochemical and stratigraphic observations by G. H. WILSON (personal communication 1973) and P. RYAN (personal communication 1973) indicate that the spilites are misplaced in the environment of the Mayo Trough. It has been proposed that they were thrust into their present position at sometime during the early Ordovician. Hence, it is possible that pre-end Silurian rotational thrusting took place, but it seems unlikely that such a rotation should be in the opposite sense, and of exactly the same amount. Hence, the final interpretation of results from the spilites must await publication of a detailed structural map. The presently available data favours pre-end Silurian thrusting with little (or no) rotation, and more complex folding than is allowed for in this analysis.

It is not possible to quote a precise age for the development of these related rotations and thrusts, which have affected most of Western Eire. The Salrock and Emlagh thrusts both post-date folding in the Mayo Trough (i.e. post Wenlock). The youngest known low angle southward moving thrusts in this are are of Mid-Devonian age, and outcrop in the Ox mountains

(CURRALL 1963). The lack of Upper Devonian material in this area makes it impossible to give any lower limit for the age of these structures.

CHAPTER 4

AUXILIARY RESULTS FROM E. EIRE AND S.W. ENGLAND.

4.1 Introduction

Apart from the two main regions reported in Chapters 2 and 3, two other small collections have been made from different parts of the British Caledonides. These are from:

a) the Ordovician volcanics of Eastern Eire, and

b) the Silurian volcanics of the Tortworth Inlier, Gloucestershire.

4.2 The Ordovician of Co. Meath and Co. Louth

Paleomagnetic collections have been made from three lower Paleozoic inliers; The Chair of Kildare, Balbriggan and Portrane, and Grangegeeth (Figure 4.1). In all cases the outcrop of the Lower Paleozoic rocks is bounded by local Carboniferous sediments. A Caradocian age for the volcanics has been established from sediments which are interbedded with, or directly overly the lavas. P. Morris and Robinson (1971) have reported remanence directions from two of these inliers (Kildare and Portrane); they concluded that the remanence in the two groups was similar and that both had been remagnetized and possibly rotated in the Permian. A collection from stratigraphically equivalent volcanics outcropping on Lambay Island gave a divergent and unexplained mean direction.

4.2.2. The Chair of Kildare

Gardiner and Reynolds (1896) describe a sequence of andesites, porphyritic basalts and tuffs from the Chair of Kildare. Overlying the volcanics is a thick limestone which has yielded a Caradocian fauna (Wright 196[illegible]).

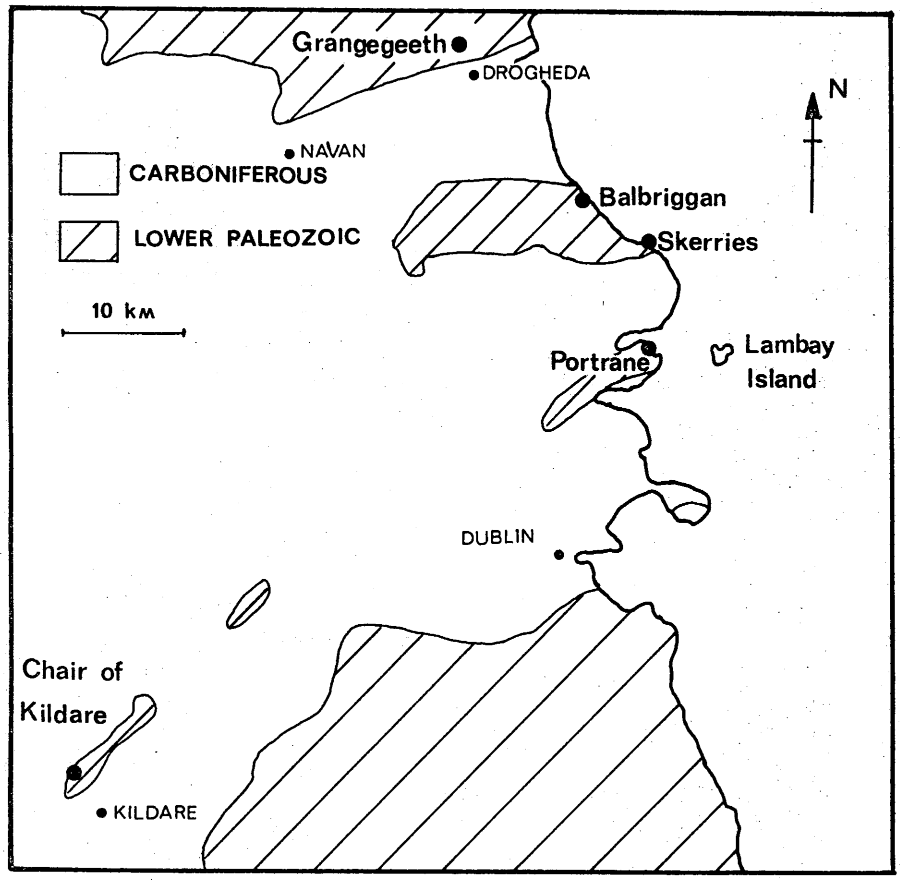


Figure 4.1. General geology and sampling localities - Eastern Eire.

Dips are steep and towards the south east. Outcrop is very sparse, as much of the area is drift covered. Only five sites were occupied, of these three are from a very large roadstone quarrry on the north side of Grange Hill. All collecting was by lump sampling, and all orientation by magnetic compass.

The total NRM site mean statistics are summarized in Table 4.1, only site 67 did not have significantly grouped remanence. Both the in situ and tilt corrected overall means are non-significant. The NRM log mean intensity of the collection at 0.57×10^{-3}G is quite high when compared to the intensity of similar Ordovician volcanic series. After the removal of an initial low coercivity VRM component progressive a.f. demagnetization mostly produced regular decay of intensity and change of direction. The exception was the sample from site 68; this showed very little intensity decay (80% of NRM intensity left after 1000 Oe. treatment), almost no direction change, and consequently a consistently high Stability Index, indicative of the ilmeno-haematite mineral series. Unfortunately no polished specimens were available to confirm the presence of haematite. As in the Eycott Group, and the Builth Volcanic Series, it seems that haematite metasomatism commonly occurs with andesite eruption, producing 'secondary' syngenetic remanence.

The sites were all cleaned in fields of 300 Oe., or less, after which all sites have significantly grouped remanence (Table 4.1). The <u>in situ</u> mean is $D = 129^{\circ}$, $I = +44^{\circ}$, $k = 11.1$, while the tilt corrected mean is $D = 177^{\circ}$, $I = +28^{\circ}$, ($k = 11.1$) corresponding to a palaeomagnetic pole at Lat. = 21°S, Long = 356°E, ($d\psi = 14$, $d\chi = 26$). These directions which differ significantly from the findings of P. Morris and Robinson (1971), are comparable to those in contemporaneous studies from England.

4.2.3 Balbriggan and Portrane

Descriptions of the shoreline outcrops at Balbriggan have been given initially by Gardiner (1899) and more recently by France (1967). The Ordovician volcanics are basic-intermediate andesites which were emplaced in a sub-aqueous environment; pillow lavas, slump breccias, and lahars are the more detailed lithologies present. Total thickness varies from 1,500m. in the south to 40m. in the north. The beds have been folded and faulted into tight anticlines and synclines. Fossiliferous deposits associated with the volcanics date the rocks as Caradocian.

Volcanics, also make up the major proportion of the rocks at Portrane, but there, there is no evidence of submarine extrusion. The andesites have been heavily altered, now containing mainly calcite, with subsidiary chlorite and epidote. Other extrusive rocks show large plagioclase phenocrysts (up to 1cm. long) in a fine grained purple matrix; this has been compared to the Lambay Porphyry (Gardiner and Reynolds 1898). The lavas are overlain by ashy conglomerates and limestones similar to the succession in the Chair of Kildare. The detailed structure of the Portrane inlier is complex, however the lavas appear to be simply tilted to the East. Shenick's Island which lies just off the Skerries (Figure 4.1) is formed mainly of Ordovician andesites. The beds are steeply inclined and partly overturned (Brück and Keenan 1970).

Total NRM statistics for these inliers are given in Table 4.3. In the calculation of overall mean directions the results from Shenick's Island are grouped with the results from Balbriggan, and the results from Portrane are treated separately. NRM site mean intensity exhibited a wide range of values. A.F. cleaned site mean statistics are given in Table 4.4. Sites whose weak NRM intensities precluded any a.f.

cleaning are included in the final analysis only if the NRM site mean was significant at the 99% level (Watson 1956 b). The <u>in situ</u> a.f.cleaned mean of the Balbriggan results is non-significant, tilt correction gives a significant mean of D = 214°, I = -4°, k = 2.8,. At Portrane both the <u>in situ</u> and tilt corrected means are significant; <u>in situ</u> mean is at D = 199°, I = -11°, k = 3.7, while the tilt corrected mean is D = 203°, I = +2°, k = 3.8 .

4.2.4. The Grangegeeth Volcanic Series

A large inlier of Caradocian sediments and volcanics outcrop between the towns of Collon, Co. Louth, and Navan, and Slane, Co. Meath. The Volcanic Series consists of tuffs, lavas and autobrecciated units. The lavas are more sodic than the contemporaneous volcanics at Bellewstown (Harper and Rast 1964) Balbriggan, Portrane, or Kildare (Sections 4.2.2. and 4.2.3.). To the N.W. the outcrop is bounded by the major NE trending Collon-Navan fault, while to the south the outcrop is terminated by the unconformably overlying Carboniferous (Harper 1952, Mantstre 1952). Because of poor outcrop and short period of time available, only two sites were collected. Both sites were collected by field drilling, and orientation was by sun compass.

Both prior to and after a.f. cleaning, the two sites have significantly grouped remanence (Table 4.6). Basing the mean on twelve samples the a.f. cleaned in situ mean is D = 180°, I = +52°, k = 26; tilt correction gives a mean of D = 193°, I = +26°, k = 26, corresponding to a virtual geomagnetic pole at Lat. = 22°S, Long. = 340°E, ($d\psi = 5°$, $d\chi = 9°$).

4.2.5 Summary and Conclusions

Although the four inliers reported in this section are thought to be contemporaneous, they yield different remanence directions. The results from the Kildare and Grangegeeth inliers can be interpreted in terms of an Ordovician geomagnetic field. While having very similar inclination they differ in declination by some 16°. This discrepancy however, is small, and possibly is a direct result of the small number of samples in these collections i.e. secular variation not being completely eliminated. Further material is required to corroborate these meagre results. The remanence directions very closely agree with similar Ordovician studies from England, indicating that this part of Eire has not suffered any end-Silurian tectonic rotation. Further verification is provided by the general NE-SW trend of geological structures, which is similar to that found in other unrotated Caledonian structures.

The Balbriggan and Portrane inliers yield similar remanence directions, which are significantly different to those of the Grangegeeth and Kildare inliers. Moreover, this difference is not only in declination but also in inclination. In addition their mean directions are poorly defined and their remanent intensities are an order of magnitude less than those found in the other two inliers. By comparison to known Carboniferous remanence directions (P. Morris 1970), it has been suggested that the Balbriggan and Portrane lavas have been remagnetized (P. Morris and Robinson 1971). Plotting the <u>in situ</u> and dip corrected site mean directions (Figures 4.3, and 4.4) of this collection shows that both plots have a strung distribution, indicative of remagnetization. The tilt corrected plot (Figure 4.3) shows that this process is only partially complete; some sites still carry an apparently Ordovician remanence direction. Because of the lack of time available, it was not possible to apply any rock magnetic

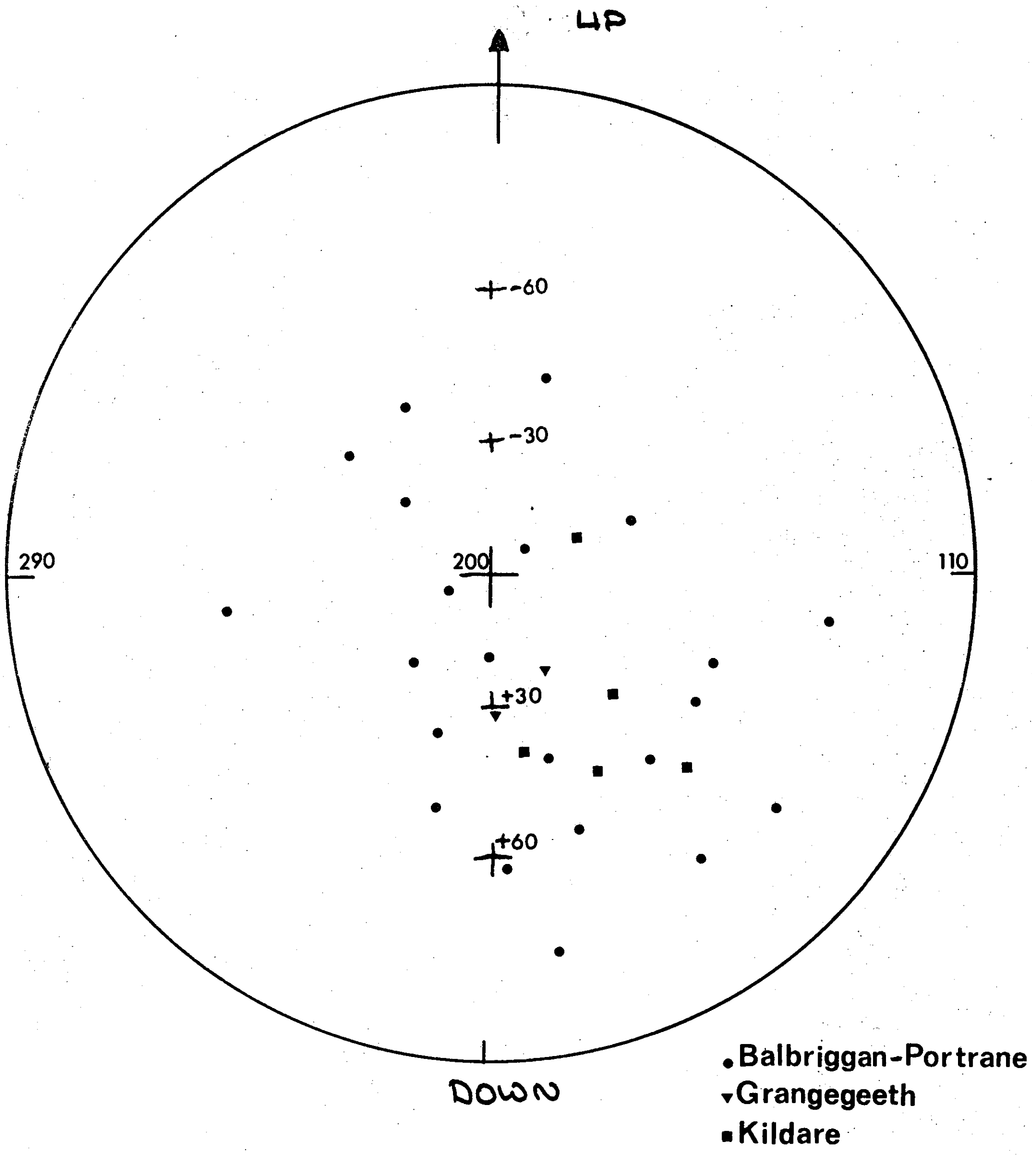


Figure 4.3. Tilt corrected site mean remanence directions. Equatorial equal angle projection.

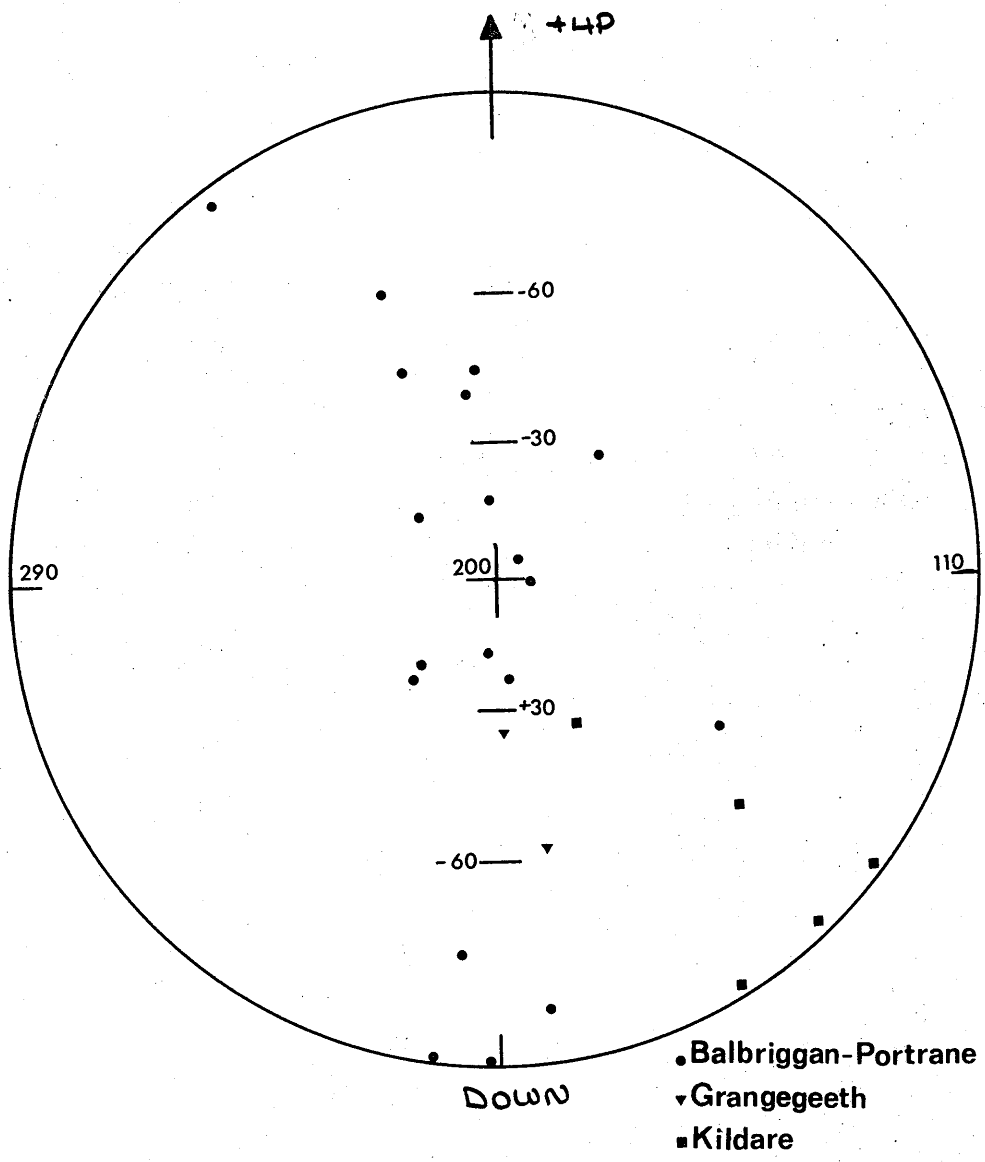


Figure 4,4. In Situ site mean remanence directions
Equatorial equal angle projection.

tests; which could have differentiated between syngenetic and post-genetic remanence. After palaeomagnetic study of the local Carboniferous sequences P. Morris (1969), also suggested that a part of north Co. Dublin had been rotated at some time during the Upper Carboniferous (or younger). The unaltered remanence directions from the Balbriggan and Portrane inliers do not appear to show any rotation.

Further studies in this region could clarify this apparent contradiction of rotations, and possibly explain why only the Balbriggan and Portrane inliers show any signs of remagnetization. An ideal starting point would be the Ordovician inlier on Lambay Island, from which P. Morris and Robinson (1971) reported a deviant uninterpreted remanence direction.

4.3 The Llandovery lavas of the Tortworth Inlier

Two andesite traps of upper Llandovery age outcrop around a shallow syncline in the Tortworth Inlier Gloucestershore (Curtis 1972). The lavas were sampled at five localities (Figure 4.5). Site 1. was collected by Drs., J. C. Briden and J. D. A. Piper, and now lies under the southbound carriageway of the M5 Motorway. Total NRM site means of sites 1. and 18. are well grouped (with the exception of a single core at the latter which is anomalous and for which orientation error is suspected; it will not be considered further). These two sites - one from each of the traps - show a high degree of stability against a.f. demagnetization. Their tilt corrected mean, errespective of polarity is D = 261°, I = $+34^{\circ}$, k = 12.0, based on eleven samples. Before tilt correction these two site means are 127° apart, after tilt correction they are 147° apart, and hence, may be regarded as of opposite polarity. Two further sites (20, 26) have total NRMs which are widely scattered about an ill defined mean close to that of site 1. Although stable to a.f. treatment within-site dispersion remains random even after attempts at a.f.

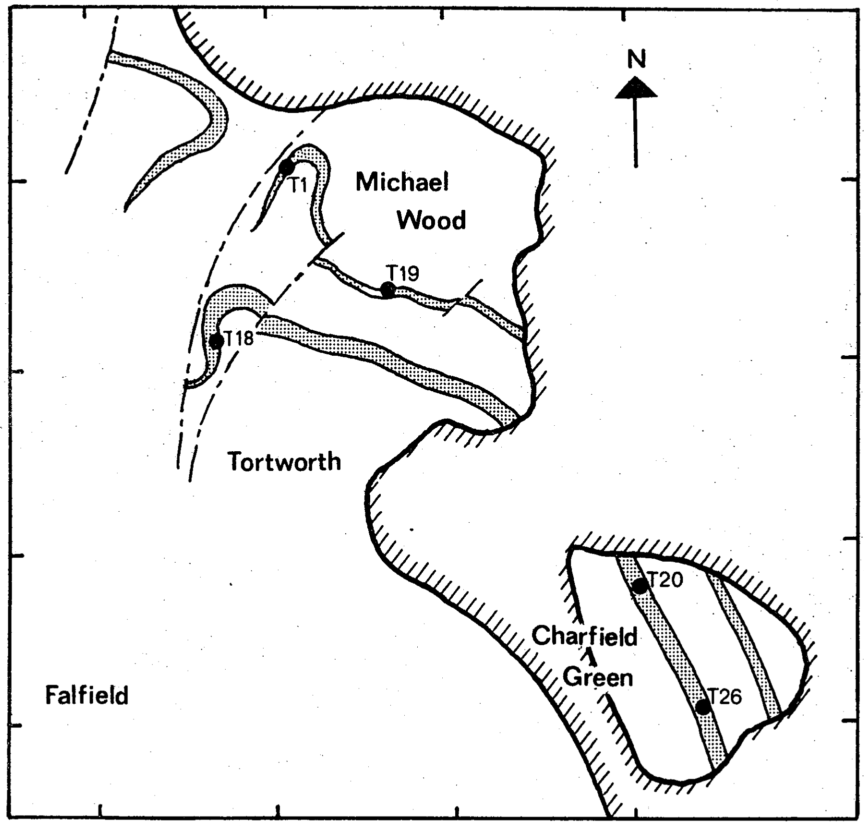


Figure 4.5 Outcrop of the Llandovery Traps and sampling localities.

cleaning. At the remaining site (19) only two hand samples were collected, and no systematic remanence has been recognised.

The westerly declination found in these rocks is the earliest record of presumed primary remanence in this typically 'Devonian' direction and provides evidence that the declination had already swung from its N/S Ordovician alignment to its late Silurian-early Devonian NE/SW alignment by the time of extrusion of Tortworth lavas in Upper Llandovery time. The basal Silurian Keratophyre of the South Mayo Trough records a similar polarity reversal therefore ratifying their correlation as proposed by Cocks _et al._ (1973). However they do not yield identical pole positions. This could be explained a number of ways e.g. failure to eliminate secular variation, inexact tilt correction, or even some partial remagnetization. With the data available it is not possible to establish which interpretation is correct.

CHAPTER 5

A REGIONAL PALAEOMAGNETIC INTERPRETATION

5.1 Introduction

Conventionally, data from a particular region is summarized by plotting polar variation as a function of time (i.e. an apparent polar wander path here-after termed 'polar path'). This assumes that for the time under consideration, the region from which collections have been made, was a single plate. The presence within the same region of orogenic belts younger than the age of the poles concerned suggests this assumption may be invalid, and that relative movements between the respective plates must be considered. Conversely, if it can be shown that the pole was relatively stationary for particular intervals, separated by periods of rapid polar shift (BRIDEN 1967), then a second method of data interpretation is to assume a fixed pole for the quasi-static period, and to note the variations about this fixed pole position.

Studies reported in Chapters 2-4 of this thesis, and others reported during the last three years have provided a vast amount of new data from the

Palaeozoic of the British Isles. This has now made possible a more rigorous palaeomagnetic discussion of polar shifts during this particular interval.

In the light of the new data, the establishment of a single British Palaeozoic polar path is discussed; from this estimates are made of polar shift and crustal drift rates. Data which do not fit a single polar path are discussed in terms of remagnetization, tectonic rotation, and anomalous remanence. A polar-shift rate curve is proposed; this is then used to establish age of intrusion where previously unknown, and to show that radiometrically based age estimates are possibly anomalous. Finally, the suggestion that the Caledonide orogenic belt represents the site of an ancient Proto-Atlantic ocean (WILSON 1966, DEWEY 1969) is discussed.

5.2 Palaeozoic polar shift relative to the British Isles

5.2.1 Interpretation of the principal data

Table 5.1 summarizes all lower Palaeozoic and Devonian data from the British Isles known to the author, which are supported by laboratory stability evidence of remanence. Among these, eighteen entries are considered as definitive, and their pole positions are illustrated in Figure 5.1.

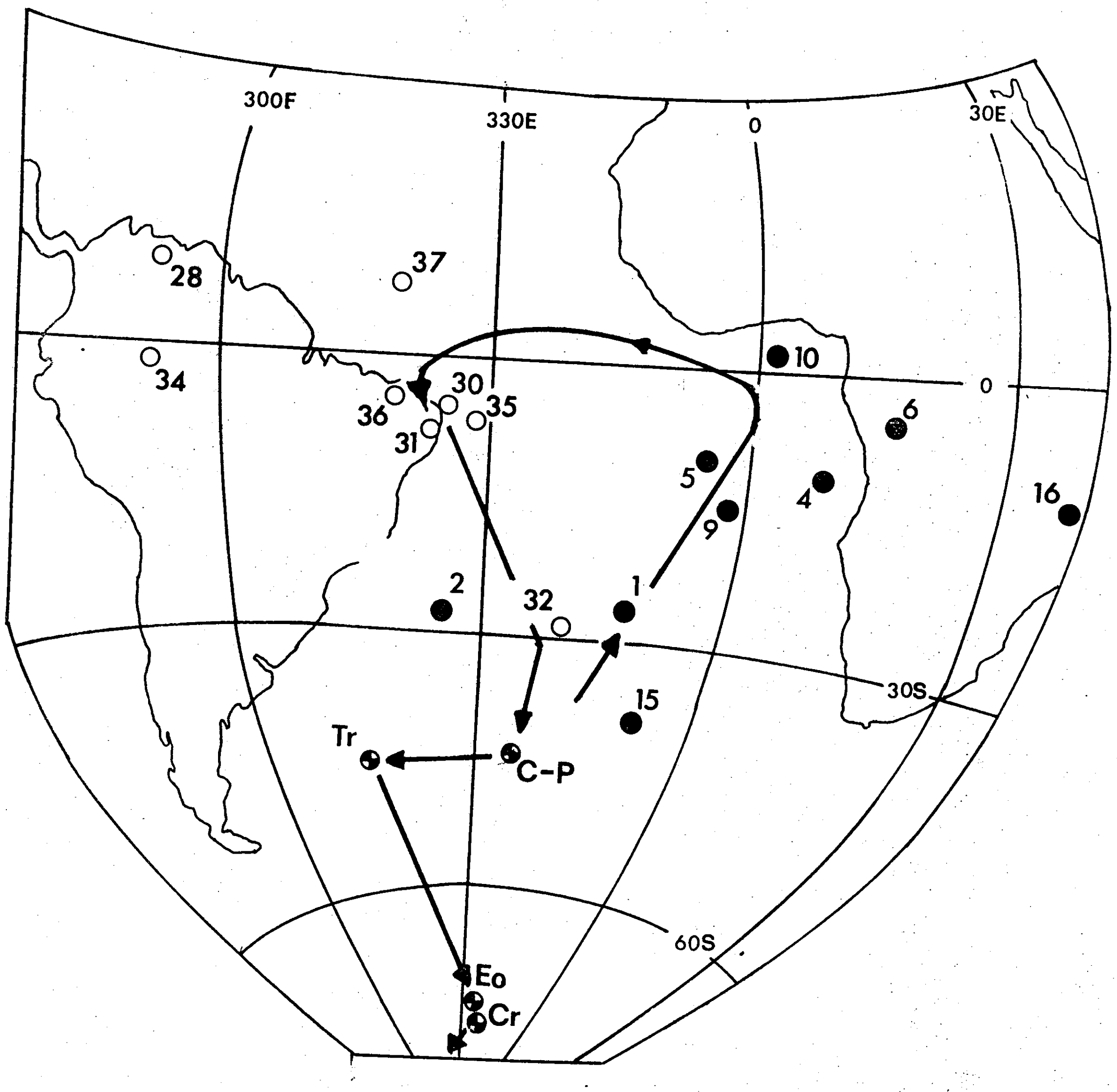


Figure 5.1. Principal palaeomagnetic data from the British Isles.Numbers referred to in Table 5.1. Full circles - Cambro-Ordovician,open circles - Siluro-Devonian poles. C-P Upper Carboniferous - Permian,Tr - Triassic, Eo - Eocene,Cr - Cretaceous poles are taken from Irving (1964).

Palaeomagnetic data from the late Precambrian and Cambrian ~~is~~ are sparse. The validity of the pole from the Caerfai Series (CREER 1957, BRIDEN, IRONS and JOHNSON 1970) is supported by a fold test of remanence and by thermal demagnetization; the pole falls close to the locally inferred Carboniferous pole. Although the precision of the Middle-Upper Cambrian Canisp Porphyry result is low, the inferred pole position is similar (THOMAS, personal communication 1973).

Reliable Ordovician data are much more numerous. The three best established poles from the British Isles are the Builth Volcanic Series, the Eycott Group, and the Aberdeenshire Gabbros; only the Eycott and Aberdeen poles are not statistically identical at the 95% level. Both sets of volcanics are of Llanvirn age, and although the age of magnetization of the Gabbros is less well defined in stratigraphic terms, it is unlikely to be much different. Because their source areas span the principal belt of post-Ordovician deformation in the Caledonides, these results suggest that later closure across this belt has been small, and hence it is legitimate at this stage to treat the whole region as though it belongs to a single plate by early-Ordovician time. The possibility that a small amount of closure is implied by these data will be deferred to Section 5.4.

The pole from the contemporaneous Borrowdale Volcanic Group, is displaced from the above group as a result of a declination difference, probably caused by rotation on a thrust plane. Syngenetic remanence is indicated by a fold test significant at the 99% level. The next result in order of age is from the Ashgillian intrusives in the Builth Inlier (PIPER and BRIDEN 1973). Its mean is not significantly different from the Eycott Group pole, although it is to the north of the earlier poles. Because of this, and because the pole from the probably contemporaneous Carrock Fell Complex lies south of the Llanvirn poles, the statisticial difference between the two results from the Builth Inlier does not appear to represent real polar shift in the interval Llanvirn-Ashgill. However, as the polar shifts involved are small, both inexact tilt correction and poor age control have possibly concealed sequential polar movements.

Other definitive results are from Western Eire. Ordovician poles from the South Mayo Trough exhibit in a small region all the possible complications that can arise from sampling in a tectonically active area. The Connemara Gabbros closely resemble the Aberdeenshire Gabbros; petrology and intrusive age are comparable.

Deformation though appears to have been somewhat different, much of the Connemara deformation took place below the Curie point (MORRIS and TANNER in preparation), whereas in Scotland no tilt corrections are applicable (apart from possibly for the insch mass) indicating a higher temperature of deformation (SHACKLETON 1948, SALLOMY 1972). Their remanence directions are significantly different, but this is mainly in declination (Section 5.4). A pole from the basal Arenig Lough Nafooey spilites is comparable to other British Ordovician results, but appears to carry a shallower inclination. Equally, the distinctive pole from the mid-Llanvirn Mweelrea ignimbrites first found by Deutsch (1969), has been fully verified. It has been shown that these discrepancies can be interpreted in terms of local tectonic effects. Hence, on current evidence the pole seems to have been stationary relative to the British Isles as a whole from basal Arenig to Ashgillian times.

From the end of the Ordovician until the late-Silurian there appears to be a break in the definitive palaeomagnetic record, but the actual duration of this break is uncertain, as the next suites of rocks studied palaeomagnetically have in general, poor stratigraphic control. Although radiometric ages are well known, the reliability and accuracy of these is questionable

DEWEY AND PANKHURST 1970 , BROWN and HUGHES in press). Both the Arrochar and the Garabal Hill-Glen Fyne igneous complexes (BRIDEN 1970) could have a cooling age as old as 420m y, but the position of this age on a stratigraphically based time-scale is uncertain. Similarly, the Foyers Granite could have been intruded at any time during the interval 400 to 480m y.

The radiometric age of the Silurian-Devonian boundary has long been in dispute (McLAREN 1969). Palaeomagnetic studies of Old Red Sandstone lavas, usually thought of as basal Devonian may have actually commenced in the Silurian. Alternatively, if the Siluro-Devonian boundary is as old as 415m y. all these rocks (Midland Valley lavas, EMBLETON 1968 McMURRAY 1968, SALLOMY and PIPER 1973 b, Glencoe lavas, McMURRY 1968 and the Lorne Plateau lavas, EMBLETON 1968) could be Devonian.
Of these studies, three (Arrochar and Garabal Hill intrusive complexes and the Midland Valley lavas) yield virtually identical pole positions. Poles from the Glencoe lavas and the Cheviot Hills Lavas (THORNING 1973)also fall in this group, their poles are statistically different to the above group of three poles. The Lorne Plateau lavas and the Foyers granite are thought to be contemporaneous, but apparently yield poles which are completely different from this Siluro-Devonian group, whose centre is at

approximately 0°, $35^{\circ}W$ on the present grid. STORETVEDT (1967) has queried the validity of poles falling in this area, but in view of overwhelming stability evidence, there can be no doubt of their reality. The Lorne Plateau lavas are anomalous because their declinations are more westerly (EMBLETON 1968), but only five sites were reported, and this result is at present under re-investigation. This leaves the anomalous Foyers Granite result; because it lies in the same structural block as some of the collections giving poles in the main group, the only explanation of its different remanence would seem to be age difference (5.4.3).

Compared with the time interval discussed above, the interpretation of Carboniferous and Permian data is not controversial. British results are few; but incorporating data from the rest of Europe (STORETVEDT 1967) indicates that the polar curve continues as drawn in Figure 5.1. Plotting these definitive data shows that the bulk of reliable pole positions fall into four or five groups; Cambrian (tentative) Ordovician (Llanvirn-Ashgill); Siluro-Devonian; Lower Carboniferous; Upper Carboniferous; and Permian.

5.2.2 Auxiliary data which refine the polar path

In addition to the principal data, Table 5.1

includes results which are regarded as second rank, either because their age is not accurately known or because their precision or accuracy (or both) is in doubt due to possible inadequacies of sampling, stability evidence, laboratory demagnetization, or structural control. Some of these data can be used to reduce the gaps in the time coverage and to elaborate the polar path of Figure 5.1.

First, the Ordovician Ballantrae Volcanics (NESBITT 1967) gave a pole at $11^{o}S$, $12^{o}W$; $\alpha 95$ was quoted as 10^{o}. But, because it is based on a collection of only twelve samples the difference from the better established Ordovician poles is unlikely to be significant in terms of polar shift. The Arenig lavas at Trefgarn (MORRIS, BRIDEN, PIPER and SALLOMY 1973) also yield a pole in the Ordovician group, and although their magnetization is probably associated with metasomatic activity, this is likely to be virtually syngenetic and hence, the 'Ordovician' pole position was reached by the Arenig.

The South Connemara Series, also probably of Arenig age, yield a pole divergent from the above goup, but which is statistically identical to the Lough Nafooey spilite pole (Section 5.5). The Derry Bay and

Glensaul Felsites carry two remanence directions, both of which are interpreted as syngenetic. The principal group agrees with the directions found in the Connemara Gabbros, while the second direction is considered anomalous and is discussed in Section 5.2.3.

Small collections have been made from four lower Paleozoic inliers of Eastern Eire. The Grangegeeth and Chair of Kildare inliers gave remanence directions thoroughly consistent with contemporaneous English results. Site mean remanence directions from the Balbriggan and Portrane inliers gave a strung distribution, thus verifying the conclusions of P. MORRIS and ROBINSON (1972), who suggested that the lavas carried an original Ordovician remanence partially remagnetized during the Permian.

Finally a small collection of three sites from a post-Caradocian dyke in the Lake District gave a pole in complete agreement with the Eycott and Builth poles. All the secondary Ordovician data therefore, strongly reinforce the suggestion that during the period Arenig-Ashgill the pole was relatively stationary; tectonic complications it would seem are largely responsible for the observed wide range of declinations.

The pole from the Knocknaveen Group (Wenlock) is based on NRM results; tilt correction was large, in some cases the beds were overturned. Overall precision of the result is low, but the pole approximates to the well established Siluro-Devonian group of poles at 0°, 35°W; especially if a pole is calculated on those sites for which tilt correction is less than 70° (MORRIS, et. al. 1973). This suggests that the pole had reached its Siluro - Devonian position by Wenlock times. The age of this shift is supported by other Silurian studies which indicate a pole position about 30° further still to the West. The pole from the Upper Llandovery lavas of the Tortworth Inlier is only based on two sites, but is supported by a reversal and a.f. demagnetization. The contemporaneous basal Silurian keratophyre of the Mayo Trough shows the same polarity reversal although not yielding an identical pole. Intrusives within the Upper Owenduff and Salrock Formations, probably of end-Silurian age also yield an in situ pole statistically identical to the Tortworth result. The Old Red Sandstone sediments of the Anglo-Welsh Cuvette and the Lorne Plateau lavas have also yielded poles 30° further to the West. In the case of the Lorne Plateau lavas only five sites were sampled, while in the Lower Old Red Sandstone sediments the stable high temperature remanence has not been well isolated. Indeed the original authors (CHAMALAUN and CREER 1964) refrained from quoting a mean direction for this remanence. It has been suggested (BRIDEN, MORRIS and PIPER 1973) that this Siluro-Devonian sub-group based on 0°, 65°W is the result of a systematic bias caused by inadequate sampling. However, the substantial amount of data reported here, shows that this westerly declination existed from Upper Silurian to Lower Devonian times, and extended from Western Eire to Scotland and Mid-Wales; a further explanation must now be sought (Section 5.5.).

The timing of the polar shift from the Lower Devonian to the Lower Carboniferous position depends on results from Middle and Upper Devonian studies. The Foyers Granite (KNEEN 1973) might be interpreted in this way, although it is difficult to believe, that it is younger than the Cheviot Hills lavas, which extend into the early Middle Devonian (MITCHELL 1972). THORNING (1973) has thoroughly refuted the contention of STORETVEDT and HALVORSEN (1968), that the remanence direction of the Cheviot lavas is indeterminate, by showing that the lavas were magnetized in the same general direction as the Midland Valley lavas.

The only data therefore which ~~is~~ are applicable to the problem of the Devonian-Carboniferous shift are two small, unsatisfactory and mutually contradictary results from the Orkneys and Shetlands. STORETVEDT and PETERSEN (1972) regard the primary magnetization of the Orkney lavas as corresponding to a pole in the 'Lower Carboniferous' position. This conclusion was based on the acceptance of results from only seven specimens out of a collection of sixty samples; their rejection criteria are not clear. Later, MORRIS, et al. (1973) presented a pole based on seven sites (36 specimens) which falls in the Siluro-Devonian group. PIPER (personal communication 1973) has re-examined the material presented by MORRIS et al. (1973) and has found that the remanence is highly unstable. Because of this and the extreme sample rejection of STORETVEDT and PETERSEN (1972), it would seem that no meaningful pole position can be found in these lavas.

Total NRM results of Upper Old Red Sandstone age from near Jedburgh (NAIRN 1960), and the Avonian (Devonian/Carboniferous) sediments near Bristol (MORRIS et al. 1973) yield poles which are statistically identical. The only reliable early Carboniferous result from the Kinghorn lavas of Scotland (EVERITT and BELSHÉ 1960) gives a similar pole near 18°S, 19°W.

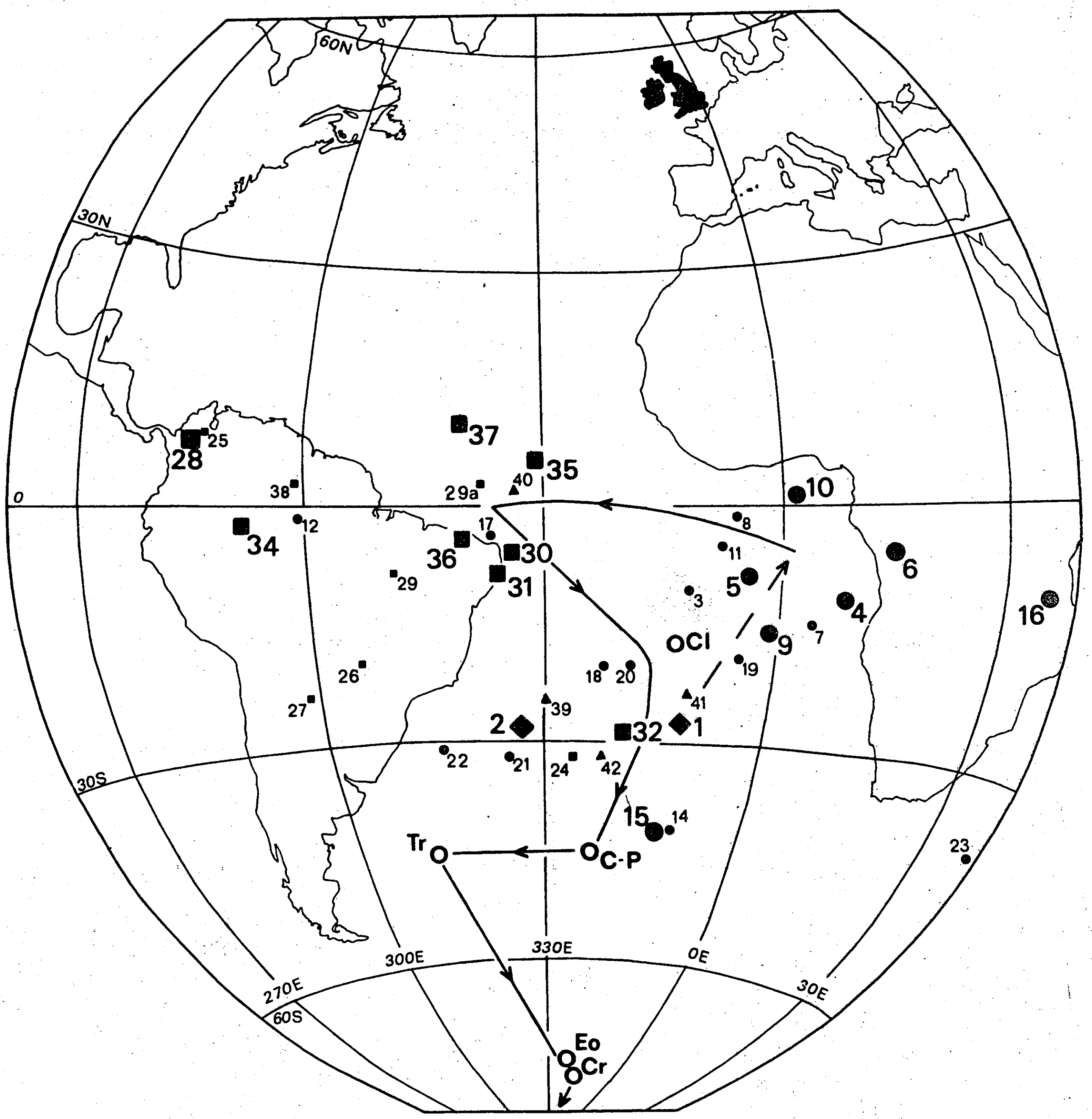


Figure 5.2. Principal and auxiliary palaeomagnetic data from th British Isles. Small symbols and numbers are auxiliary data. Numbers refer to Table 5.1. Diamonds (◆) -Cambrian, circles(●) - Ordovician, squares (■) - Silurian - Middle Devonian, triangles (▲) -Upper Devonian -Lower Carboniferous(ce).

Because Lower Carboniferous data for Western Europe are few it is not clear whether polar shift proceeded continuously from the Devonian until the pole reached the vicinity of 44°S, 22°W in the Upper Carboniferous, or whether two distinct drift episodes occurred. Results from the Russian platform indicate a continuous shift.

Figure 5.2 illustrates the end product of this discussion, it gives the best interpretation of the currently available Paleozoic data.

5.2.3. Anomalous directions

A number of remanence directions found in these collections were considered 'anomalous' when compared to known Paleozoic field estimates (Table 5.2). Mostly these directions have steep inclinations (positive and negative); possibly steep inclinations predominate as they are most easily spotted. In all cases the rocks are of igneous origin, and hence it is assumed that they record the instantaneous local geomagnetic field. Results with 'anomalous' directions have been found from Lower Ordovician to earliest Carboniferous. Possible explanations for these directions fall into two groups, (a) primary remanence; large secular variation, polarity transition directions, or (b) secondary remanence drilling induced remanence, IRM, VRM, or remagnetization as a result of chemical or mechanical alteration of the rock. Where syngenetic remanence has been established for the principal group of results, to produce a secondary remanence in the 'anomalous' group requires either (a) localised remagnetization, or (b) some locally developed magnetic property.

Detailed studies of the behaviour of the Earth's field during a polarity transition have been given by van ZIJL et al. (1962), WATKINS (1969), and McELHINNY (1971). In most cases the intensity decreases by a quarter to a fifth of the normal value, while the direction exhibits rapid and 'erratic' shifts. Some of the anomalous directions found in these studies fulfill these requirements. The Upper Llandovery keratophyre of Killary Harbour shows both polarities, and also intermediate directions, which have a 90° declination displacement from the dipole fields, and carry significantly weaker magnetizations. The Cockermouth lavas although not exhibiting both polarities, do have sites with lower intensity and significantly different directions to the accepted Carboniferous mean direction. Apart from possibly the dykes intruding the Eycott Group (Section 2.5) all other anomalous results are from Ordovician volcanics. It has been shown that during the Ordovician period, apparent polar shift was very small and irregular, and that there are a number of polarity reversals (RODIONOV 1966). CREER and ISPIR (1970) have shown that it is possible to classify a number of Tertiary polarity transitions into complex and simple types; corresponding to the effects of one or more non-dipole components. They report two important properties of polarity transitions; (i) the path of virtual geomagnetic poles may be the same for the same polarity transition even if the sites are from geographically separate regions, and(ii) that the path of polarity transitions in the same geographical region may be repeated during later transitions. If this is applicable to the Ordovician and the transitions are 'simple', then plotting all known anomalous directions on the same hemisphere should produce a planar meridional distribution between the remanence directions known from principal Ordovician date (Figure 5.3).

The intensity of many of the anomalous specimens is comparable to that of the principal data, contradicting the suggestions that polarity transitions are associated with geomagnetic field intensity reductions.

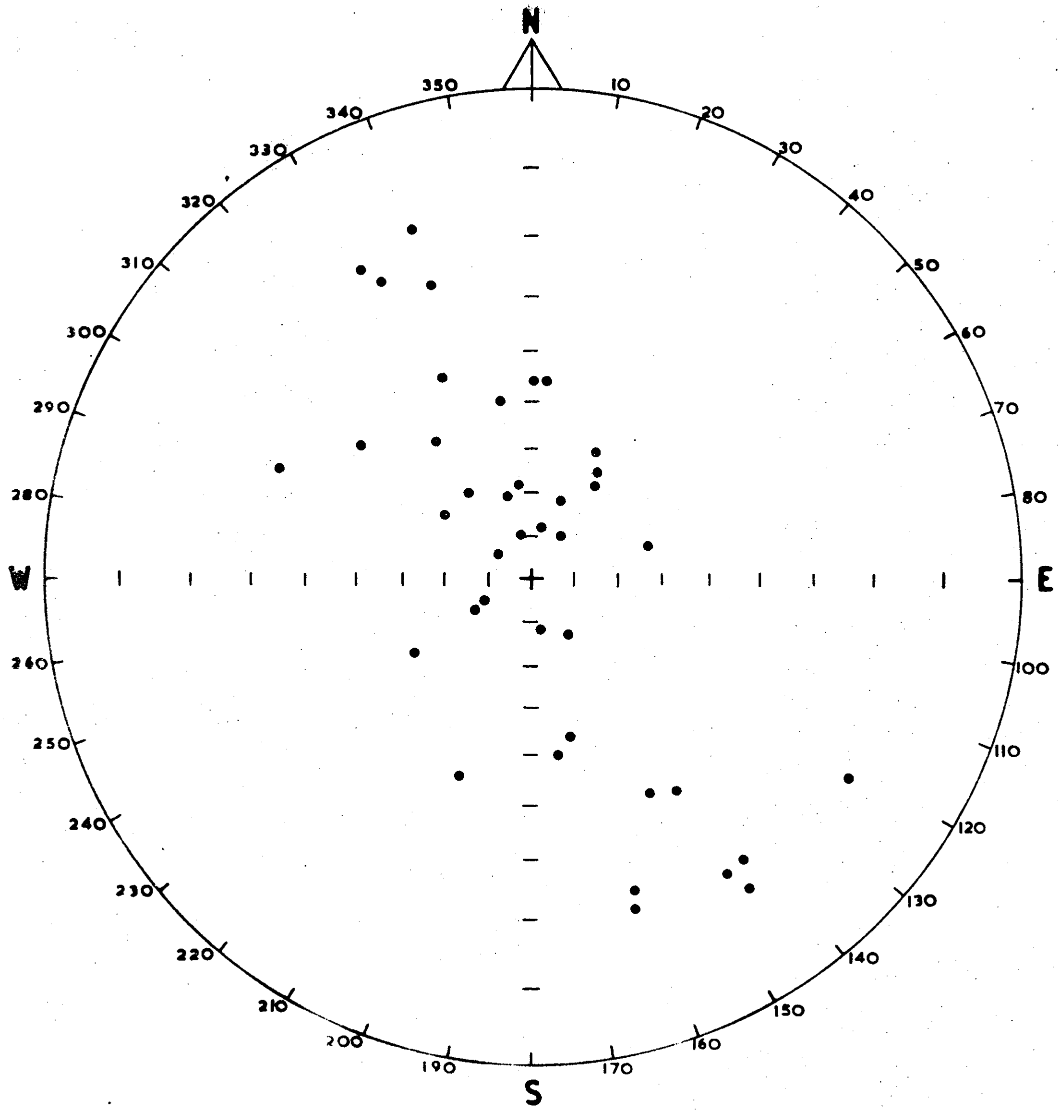


Figure 5.3.Plot of tilt corrected 'anomalous'site mean remanence directions.Equal angle stereographic projection.

CARMICHAEL (1967) and SMITH (1967) have shown that during the Lower Paleozoic the main dipole moment was approximately 10% of the present value of the Earth's magnetic field. There is no evidence to show whether the non-dipolar field exhibits ~~similar~~ intensity fluctuations similar to ~~as~~ the main dipole field. Polarity transitions provides a possible explanation for the 'anomalous' directions. Detailed field and laboratory studies of material from a region where both principal and anomalous directions are intermingled, would be most useful.

Another possible explanation, is that the anomalous directions are produced by the field collecting technique. Drilling-induced remanence has been discussed by KUSTER (1969), and examples have been given by SALLOMY (1972). At each palaeomagnetic site a number of samples are drilled; in the ideal case the directions of these holes are randomly distributed. If for each sample some directional parameter is represented by a unit vector, then the vector sum of the unit vectors (R) gives the mean direction of that parameter for a particular site. The sum of the drilling direction vectors is defined as R_{holes}; the sum of the relative to core remanence directions as R_{cores}; and the sum of the <u>in situ</u> remanence directions as $R_{\underline{in\ situ}}$. If the holes have been drilled randomly, then for purely syngenetic remanence $R_{\underline{in\ situ}} > R_{cores} \approx R_{holes}$. While for purely axial drilling induced remanence ^{R}cores $>$ ^{R} in situ $\approx$ ^{R} holes. In cases where the drilling induced remanence is not strictly axial and where ^{R} holes is large (i.e. drilling direction is well-grouped) the second relationship may not apply. Table 5.3 gives ^{R} cores, ^{R} holes, and ^{R} in situ for the Borrowdale Volcanic Group only sites 71, 82 and 84 fulfill the requirements for drilling induced remanence, and of these only for site 84 is this probably significant. Burmester (1970) has proposed a method for cleaning affected samples by pickling in conc. HCl, based on the assumption that drilling remanence is produced by contamination from the steel core barrels. Attempts were made to 'clean' samples from site 84 using methods described by KRAFT and FISCHER (1960) and PRASAD (1969). In the former case the samples are boiled with a 5% Br_2 solution in methanol, in the latter case the samples were boiled in a 10% aqueous $CuSO_4$ solution. Neither method produced any change of specimen remanence direction. Furthermore, the work of SALLOMY (1972) showed that ^{R}cores increased with depth down the Mocharas borehole, suggesting that the remanence is more probably a thermal rather than a surface contamination effect. There is no evidence for drilling induced remanence in these collections.

Possibilities 3 and 4 can be treated together, RIMBERT (1956) and KOBAYASHI (1959) have shown that the typical response of TRM and CRM to a.f. demagnetization is totally different to that of VRM and IRM. In most cases the anomalous sites do not exhibit distinctive a.f. demagnetization characteristics, so although an odd site may be explained in this manner, it is not applicable to the group as a whole

Finally, because some of the sites occur close to fault planes (Derry Bay Felsite, Borrowdale Volcanic Group), explanations in terms of local frictional heating, or chemical alteration must be considered. Again, these sites are not magnetically distinct from either the other anomalous results, or the principal data; hence this suggestion seems ill-founded.

5.3 PaleoZoic relative movement within the British Isles.

Closure across the Caledonide fold belt has been advocated on a number of geological grounds. WILSON (1966, and later WILLIAMS 1969) proposed zonal distributions of fossil types, which they suggested was caused by Ordovician provinciality. DEWEY (1969) took a much more comprehensive approach, and proposed a plate collision model for the Caledonide orogenic belt, based on sedimentary, volcanic and structural evidence. Since, discussion has been limited mainly to the number and direction of subduction zones required to explain various local stratigraphic relationships (FITTON and HUGHES 1970, MITCHELL AND READING 1971, BAKER 1973, GUNN 1973, GARSON and PLANT 1973). None of the techniques hitherto employed provide any quantitative measure of the proposed separation between the two continental masses. By using a palaeomagnetic analysis not only is it possible to give some measure of the separation, but in conjunction with geological evidence it is possible to date episodes of deformation, associated with closure of the proposed ocean.

The two studies reported from the Cambrian of the British Isles span the range of the Caledonide orogenic belt. The Canisp Porphyry (THOMAS personal communication 1973) outcrops on the North-West foreland, West of the Moine thrust. The Caerfai Series

(BRIDEN, IRONS, and JOHNSON 1970) although lying on the southern foreland of the Caledonide belt, is also well within the region of Hercynian deformation. The difference between these poles is almost entirely in longitude, explainable purely in terms of tectonic rotation. There is some evidence from the Silurian of South Wales and Gloucestershire, which appears to indicate a 30° post-Silurian clockwise rotation (Section 5.5).

The Ordovician data is much more conclusive. On the Southern side of the postulated ocean the two principal studies from the Builth Volcanic Series and the Eycott Group are statistically identical with greater than 99% probability. The latitudes and orientation which they imply are illustrated in Figure 5.4, these are supported by the data from the Carrock Fell Complex, Trefgarn and Ballantrae. On the northern side only the Aberdeenshire Gabbros pole is suitable for statistical comparison because many of the other results are suspected to have suffered considerable local rotation. Comparing the mean directions in the Aberdeenshire Gabbros, with the overall Builth/Eycott mean, there is less than 95% probability that they are identical (WATSON 1956 a). A recalculated pole for the Foyers granite (5.4.3)

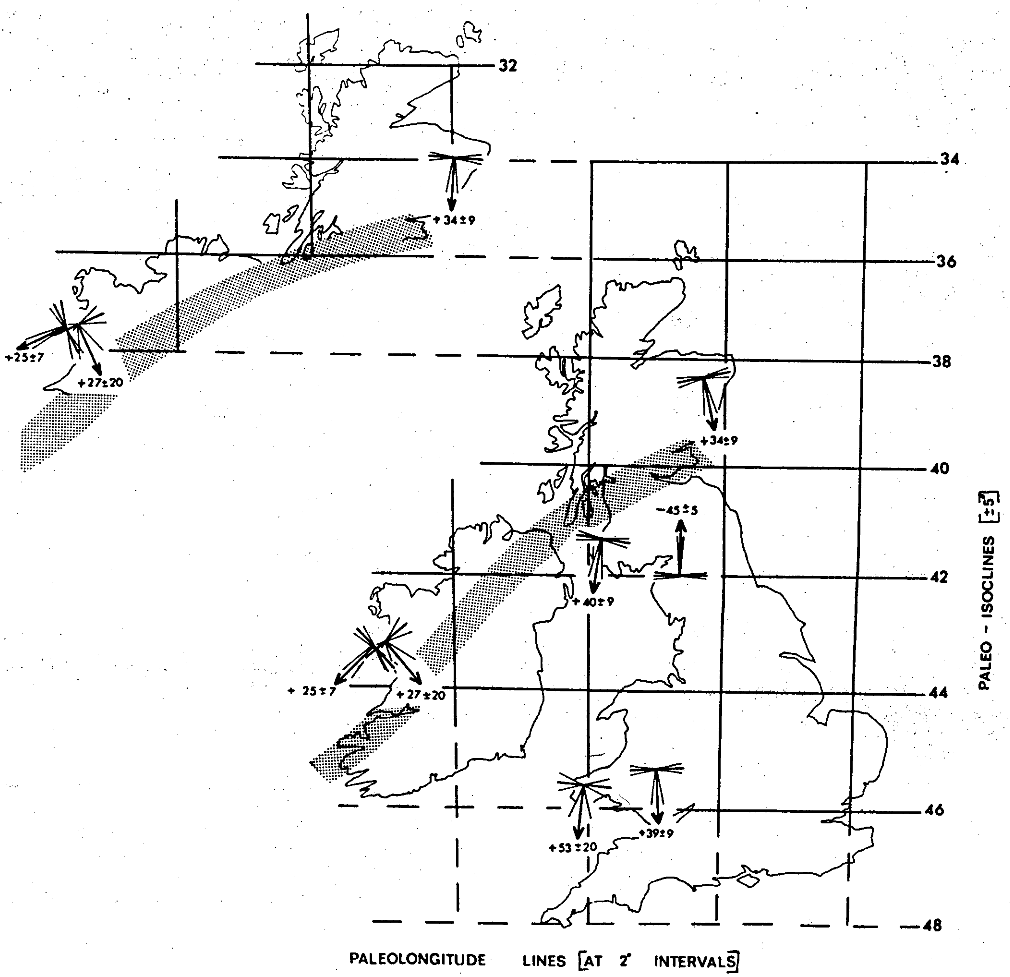


Figure 5.4 Lower Ordovician continent distribution based on palaeomagnetic data.

which also belongs to the northern block, is not significantly different to the Aberdeenshire Gabbro pole. Again the displacement between the two blocks is mainly longitudinal, in this case approximately 10°. Latitudinal separation is very small, hence estimates of closure across this belt are solely limited to errors in the definitive palaeomagnetic poles. Typically these are around 10°, hence a best estimate of the maximum closure across the Caledonide ocean is approximately 1000 km. However, it is possible that a much wider Palaeozoic ocean existed further to the West (CHIDESTER and CADY 1972). Ordovician studies from Western Eire have generally yielded shallower inclinations than contemporaneous studies from Britain. After allowing for the postulated 1000 km. latitudinal separation, the inclinations observed in the Connemara Gabbros, the Mweelrea ignimbrites, the Glensaul and Derry Bay Felsites fit their proposed palaeolatitudes better than if no closure is inferred. A best fit, though would place Western Eire in even shallower palaeolatitudes, suggesting an ocean some 1800 km. wide in this region. Further support for a widening of this ocean to the west is provided by the overall disagreement between British and American Ordovician palaeomagnetic data (McELHINNY and OPDYKE, in press). Most of the Siluro-Devonian poles fall in the vicinity of 0°, 35°W. Poles which fall 30°, further to the West have been attributed to local (Lower?) Devonian rotation. HARLAND and GAYER (1972), have interpreted this same period as a time of major transcurrent movements within the Caledonide belt. A block caught between two such faults on which movement is taking place at different rates will tend to be rotated. The rate and direction of fault movement may change along its length, producing different rotations, tensions, and compressions at various points along the orogenic belt (Harland 1971).

As shown in the previous paragraphs there is little palaeomagnetic evidence for a major ocean on the site of the British Caledonides. From the very limited data available it appears that the ocean which varied in width along its length was at its maximum extent at some time during the Lower Ordovician. Opening was small comparable to the present day (c.f. Mediterranean and Red Sea ocean basins), (HARLAND 1967). However, it may be generally true that large scale crustal drift, involving oceanic plate consumption, significantly predates the orogenesis when two continental plates collide. If this is so, large scale closure across the British Caledonides might have occurred during late Pre-Cambrian or Cambrian time, and palaeomagnetic data are not yet available to evaluate this.

5.4 Palaeomagnetic dating

5.4.1. Introduction

To date rocks or geological events by palaeomagnetism, one aims to date each component of NRM. Most rocks studied here appear to carry only a single component of stable remanence, whose age is estimated by comparison of its pole position, with a well-dated polar path. An example is Figure 5.5 in which age of host rock is plotted against arc-distance along the polar path. Since the age of remanence can never exceed rock age every observation must plot either on or to the right of the thick lines which are therefore the best estimates of polar shift rate.

5.4.2 Age of the Carrock Fell Complex

In favourable cases rocks whose geological age is uncertain may be precisely dated palaeomagnetically e.g. the Carrock Fell Complex. Two modes of intrusion were considered for the Complex; if it had been emplaced as a sill and subsequently rotated about its present strike to attain its current position, then the stable remanence would not match any inferred Ordovician, or younger palaeomagnetic field. If, on the other hand, the Complex was emplaced as a dyke-like body subject only to slight tilting then the magnetization matches the locally determined Ordovician field. Hence the palaeomagnetic evidence emphatically favours the second alternative.

It is important to establish the limits of this age estimate. As the characteristic 'Ordovician' field direction (Figure 5.5) persisted no later than the earliest Silurian, a minimum age for the Complex is defined by the magnetization. A geological estimate for the minimum age is about 400 my., the approximate age of intrusion of the Skiddaw Granite, which metamorphoses the Carrock Complex. The maximum age may be roughly estimated as end-Llandeilo on tectonic evidence, if about 10-15 my. are required to fold the Eycott Group to dips approaching the vertical prior to emplacement of the Carrock Fell Complex (EASTWOOD et al. 1968). Hence the age of the Complex may now be confined to the Caradocian or Ashgillian, an interval of 20 my., compared to the purely geological estimated interval of around 80 my.

5.4.3 Age of secondary magnetization

If a point plots well to the right of the main polar shift-rate curve, then remagnetization at a later date is inferred. The magnetization of the Fishguard Volcanic Series (MORRIS et al. 1973), appears to carry a Siluro-Devonian remanence, associated with Caledonian orogenesis. The Skomer Volcanics, the Ashprington Volcanics, and the basic intrusives of Devon all lie well within the Hercynian fold belt, and appropriately carry a Permo-Carboniferous in situ remanence. Each of these sequences appears to have been remagnetized during orogeny each carries only a single polarity of remanence, possibly as result of synchronous magnetization within each sequence. This is consistent with the simple polar path described in Figure 5.1.

It remains to consider the Foyers granite; from Figure 5.1 its remanence could most easily be explained in terms of Cambrian/early Arenig or late Devonian/Lower Carboniferous poles. It is unlikely that the cooling age of the Complex is more than 480 my., and therefore older than the cooling age of the Aberdeenshire Gabbros.

A magnetization younger than Mid-Devonian seems to be precluded by contact and conglomerate tests. KNEEN (1973) has suggested that the unconformably overlying Middle ORS sediments yield an identical direction to the granite yet time must be allowed for the removal of overburden prior to the exposure of the granite at the Earth's surface. If this process required more than 10 my., then the radiometric age for the intrusion (400 $\mp$ 18 my.) as suggested by MILLER and BROWN (1965) is verified. Yet, it has been shown that contemporaneous studies from the Garabal Hill, and Arrochar Complexes, the Cheviot Hills, and Midland Valley lavas yield consistent and significantly different palaeomagnetic pole positions. Unless Mid-Devonian remagnetization is invoked, it must be concluded that the Foyers Granite was intruded at some time in the Lower Paleozoic, in which case the pole position calculated by KNEEN (1973) is anomalous. Discussions of the regional distribution of K/Ar ages have been given by DEWEY and PANKHURST (1970) and BROWN and HUGHES (in press), in both cases an age of approximately 460 my. is proposed for the Foyers granite. Further, a recent Ar^{39}/Ar^{40} study (CHARLTON personal communication 1973) has given a plateau age of c.460 my. Recalculating KNEEN's data for the granites and the Devonian sandstones yields two significantly different pole positions. A pole for the granite using data from the granodiorite (6 sites) and the monzonite (3 sites) yields a pole at Lat = 18°N, Long = 170°E ($d\psi$ = 14°, $d\chi$ = 25°), which falls very close to the Caerfair Series pole. While a pole from the five Middle Devonian sites is at Lat = 29°N, Long = 146°E, ($d\psi$ = 14°, $d\chi$ = 29°), which agrees closely with the 'Lower Carboniferous' poles of Figure 5.1.

5.4.4 Ages and rates of polar shift

The rate of polar shift with time is best estimated by a curve which in Figure 5.5 has a positive or zero gradient, and which 'overlies' all the data points, taking into account the uncertainties in age and pole positions. The 95% errors in pole position are depicted by the vertical bars in Figure 5.5, and the age uncertainties (which in some cases are somewhat arbitrary), by horizontal bars. The points depicted by dotted lines are considered invalid (e.g. the Orkney and Shetland lavas, and the Foyers granite). Other poles appear to fall on the polar path (Figure 5.1) at an age much younger than their age of remanence due to local tectonic rotation (e.g. the

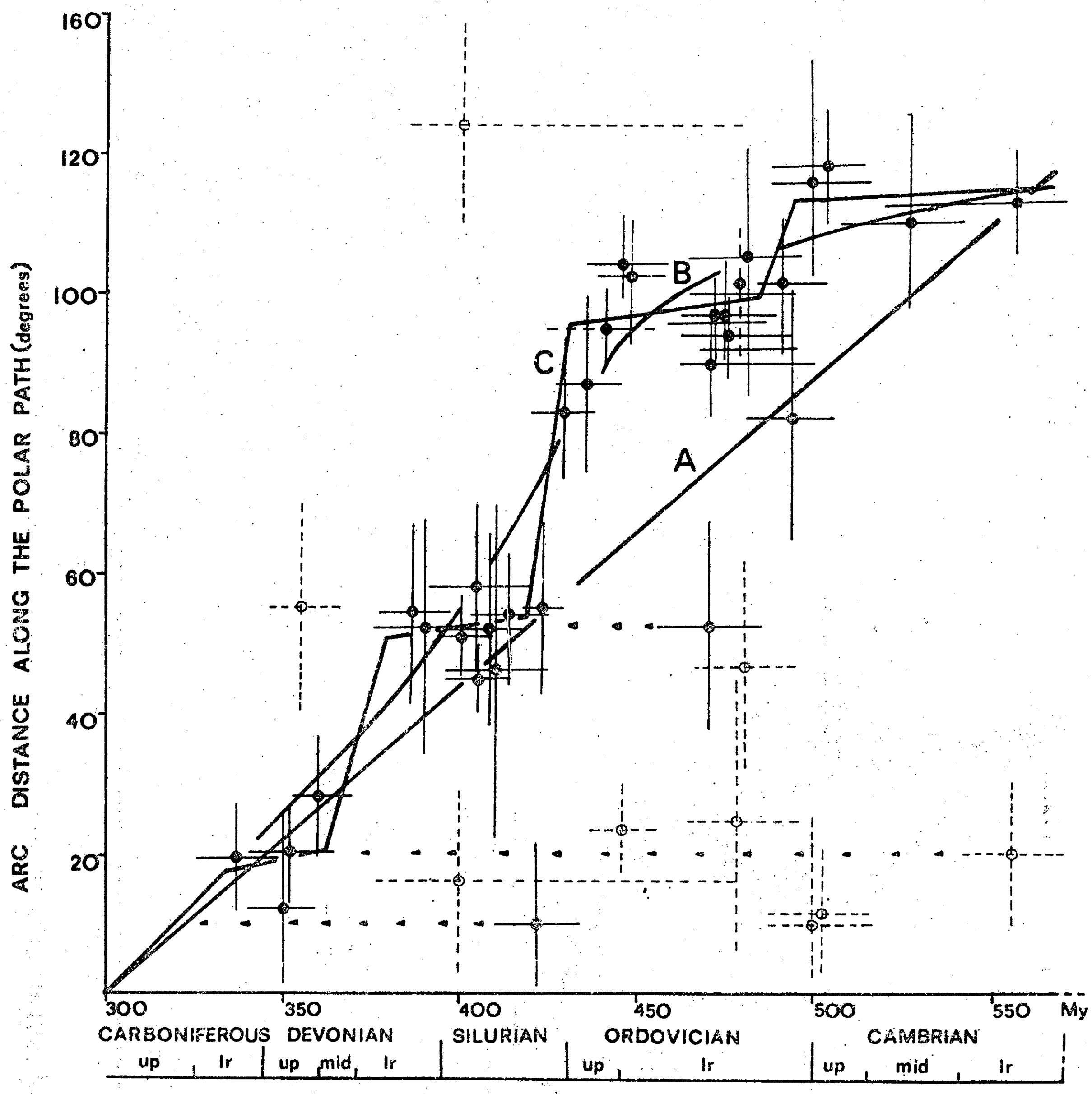


Figure 5.5. A polar-shift rate curve for the Palaeozoic. Lines A,B,and C allow for differing amonts of episodic shift. All data points are calculated from figure 5.2. Horizontal bars indicate the errors in age estimates,while the vertical bars indicate the errors in pole positions.The dotted points are considered anomalous,possibly due to remagnetization or tectonic rotation.

Connemara Gabbros, the Derry Bay and Glensaul Felsites).

The most uniform curve which fits the data is labelled 'B', this accommodates most of the data. The slope of the curve corresponds to shift rates ranging between 0.3 and 2.0 degrees per million years. The data can however be better fitted by an episodic drift curve; the age-distribution of the data is less irregular than the distance distribution. An extreme example of episodic shift is shown by line 'C', this implies drift rates varying from near zero to 4.0^{o}/my. The true curve is most likely to be intermediate between 'B' and 'C'. The curves imply more rapid polar shift in the later Palaeozoic than the Cambrian and Ordovician, but as noted previously Cambrian data is sparse.

It is not correct to equate the rate of polar shift with the rates of crustal drift of the source locality. If a locality 'S' and paleomagnetic pole 'P' are displaced to positions 'S' and 'P' by a small rotation through an angle about a Eulerian pole 'E' (BULLARD, EVERETT and SMITH 1965) then;

$$\frac{\text{Crustal drift}}{\text{Polar shift}} = \frac{SE}{PE}$$

Thus polar shift and crustal drift rates are equal when the Euler pole is equidistant from the source and the paleomagnetic pole. When E is close to S then polar shift is magnified by local rotation of the source. Conversely as E approaches the pole P crustal drift becomes indeterminate. In the simplest case SE=PE=90°, and the crustal drift follows the paleomeridian through S and is evaluated from the change in paleomagnetic latitudes. This provides a minimum estimate of the amount of crustal drift ($d\lambda/dt$ degrees of latitude/my.), to which must be added the amount of local rotation inferred from change in declination (dD/dt degrees/my.).

Estimates from curve C assuming a 10 my. long drift episode for the shift near the Ordovician-Silurian boundary are $d\lambda/dt = 0.4^{\circ}$/my. (= 4 cm/yr.) with $dD/dt = 3.4^{\circ}$/my Hence, bearing in mind the statistical errors, the polar shift could be entirely a result of local rotation of the British Isles. For the shift within the Devonian the calculation gives crustal drift = 15cm/yr. and rotation of 2.7°/my., implying that this polar shift was mainly related to substantial drift of the British Isles at a rate which would be regarded as fast by present day standards. Apparent polar shift rates for both of these episodes are about 2°/my., and although drift at 20cm/yr (or more) could equally well explain these shifts, the preceding discussion shows that such extreme velocities are not necessary.

5.5 Local tectonic rotations

Orogenesis produces many effects which can modify the syngenetic remanence direction of a particular rock. Local remagnetization has already been discussed; another possibility discussed here is local tectonic rotation. The mean of the Eycott Group, the Builth Volcanic Series, and the Aberdeenshire Gabbros is taken as a reference point to which all other Ordovician directions can be compared (Figure 5.6). Ordovician data from the Mayo Trough fall into three groups; (a) Connemara Gabbros, Derry Bay and Glensaul Felsites, which lie about 40° west of the reference point, (b) the Lough Nafooey spilites, the South Connemara Series, which apparently show no rotation, and (c) the Mweelrea ignimbrites which lie approximately 40° east of the reference point. Further, all Silurian data from within the Trough fall into an extremely westerly group, approximately 35° west of the remaining Siluro-Devonian results (Figure 5.7). The general strike of the Caledonide belt is NE-SW, but in the Mayo Trough this becomes E-W, a 45° clockwise rotation. If the strike was rotated into this direction during the late Silurian or early Devonian, then correcting the remanence directions for this rotation, brings group (a) of the

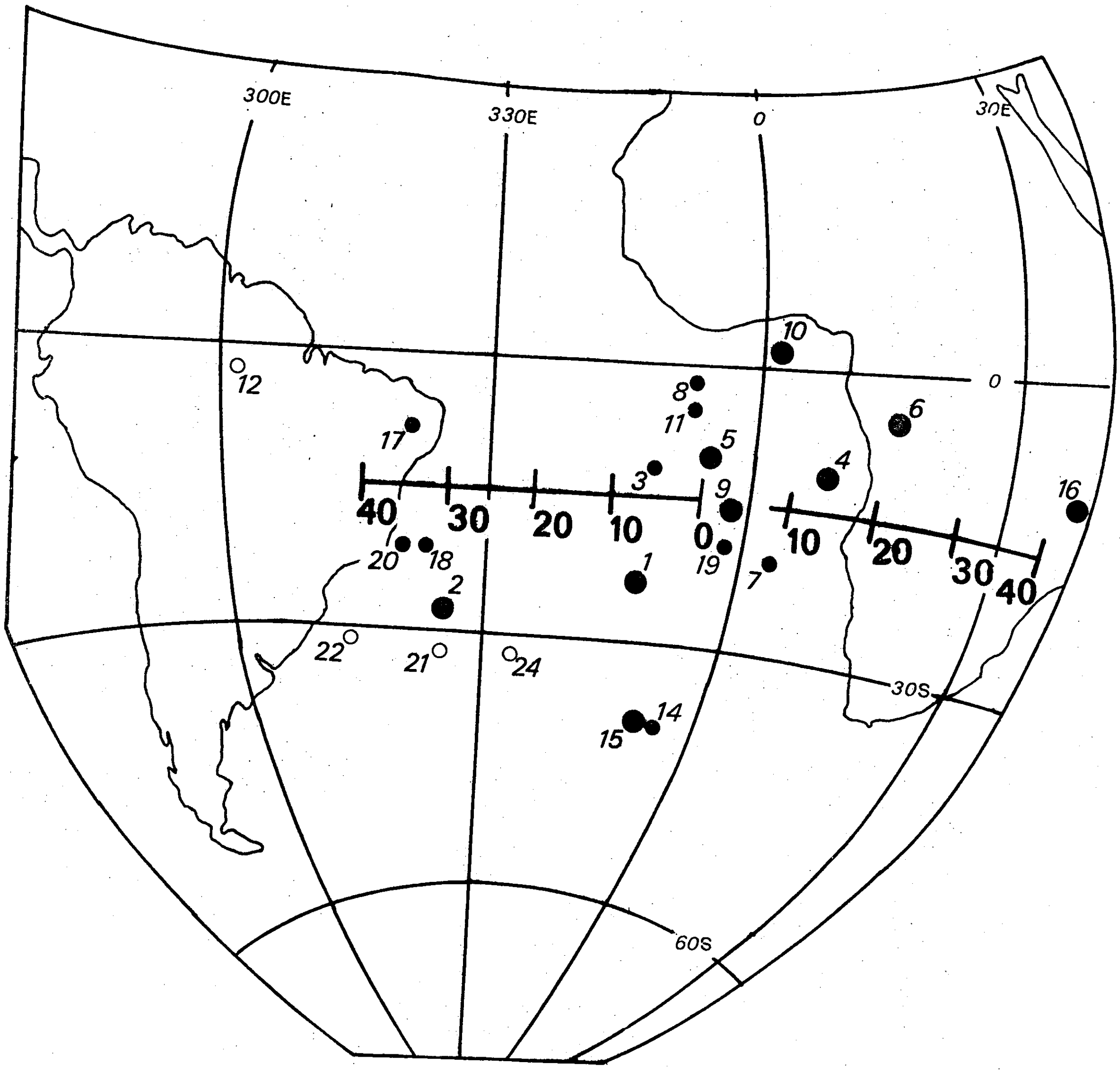


Figure 5.6. Ordovician tectonic rotation. Open circles are considered remagnetized.

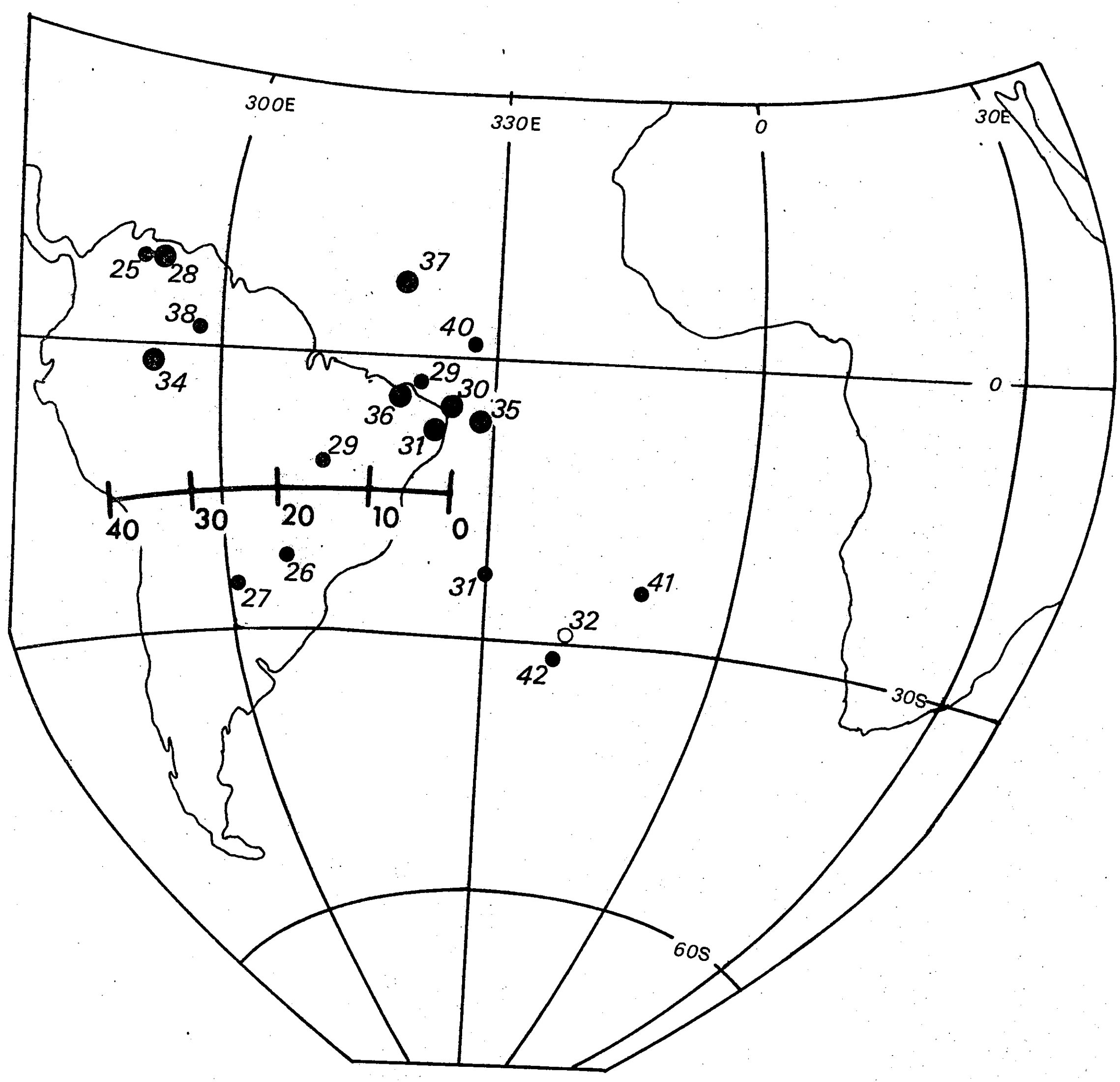


Figure 5.7 Postulated Silurian tectonic rotations.

Ordovician data and all the Silurian data into close agreement with their respective groups.

The Mweelrea ignimbrites (Group 'c') lie directly above the Salrock thrust, which produced a 40° anti-clockwise rotation. As the thrust is dated as late-Silurian, it would seem that the mechanism responsible for the rotation of Connemara also produced the Salrock thrust.

It remains to consider the anomalous direction found in group (b). Geochemically and stratigraphically G. H. WILSON (personal communication 1973) has shown that the spilites are misplaced in the Mayo Trough. Hence one possible explanation is that the spilites were thrust into their present position, and that during this thrusting they suffered an anti-clockwise rotation, which was anulled by the later end-Silurian rotation. Significantly the contact between the spilites and the underlying country rock is never seen. A second explanation is that the spilites are plunging at approximately 30° to the East. Correcting for this brings the spilite results into much closer agreement with the Group (a) directions. As yet no detailed structural map of the spilites has been published, and hence application of any tilt correction is tentative.

Exceptional declination anomalies in the Mayo Trough are confined to the area south of the Highland Boundary Fault (PHILLIPS, RICHARDS and DEWEY 1972). The Knocknaveen Group of Louisburgh, although having an E-W strike, yields a pole which is thoroughly consistent with data from Great Britain. All the Silurian rocks of Louisburgh lie on a number of northerly dipping thrust planes, rotation on which has compensated for the 40° clockwise regional rotation.

Figure 5.7 shows that the Siluro-Devonian data falls into two groups, one separated from the Ordovician pole positions by 30° to the west and one by 65°. Because the western Eire data formed the majority of the more westerly group, it now remains to be seen if all other results of this group can be explained in terms of local tectonic rotation. The Lorne Plateau lavas belong to the same tectonic block as the Glencoe lavas, and the Garabal Hill and Arrochar complexes, all of which give a pole in the more easterly group. Tectonic rotation would seem impossible. The only explanation would seem to be that the estimated direction is incorrect, the quoted pole for the Lorne Plateau lavas is based on only five sites.
Work in progress at the moment has shown that the lavas give a well-defined tilt corrected pole (from 15 sites)

which is statistically identical to all other known Siluro-Lower Devonian results. (LATHAM/1973 personal communication). Hence all data from the Lower Devonian volcanics of Scotland are mutually consistent.

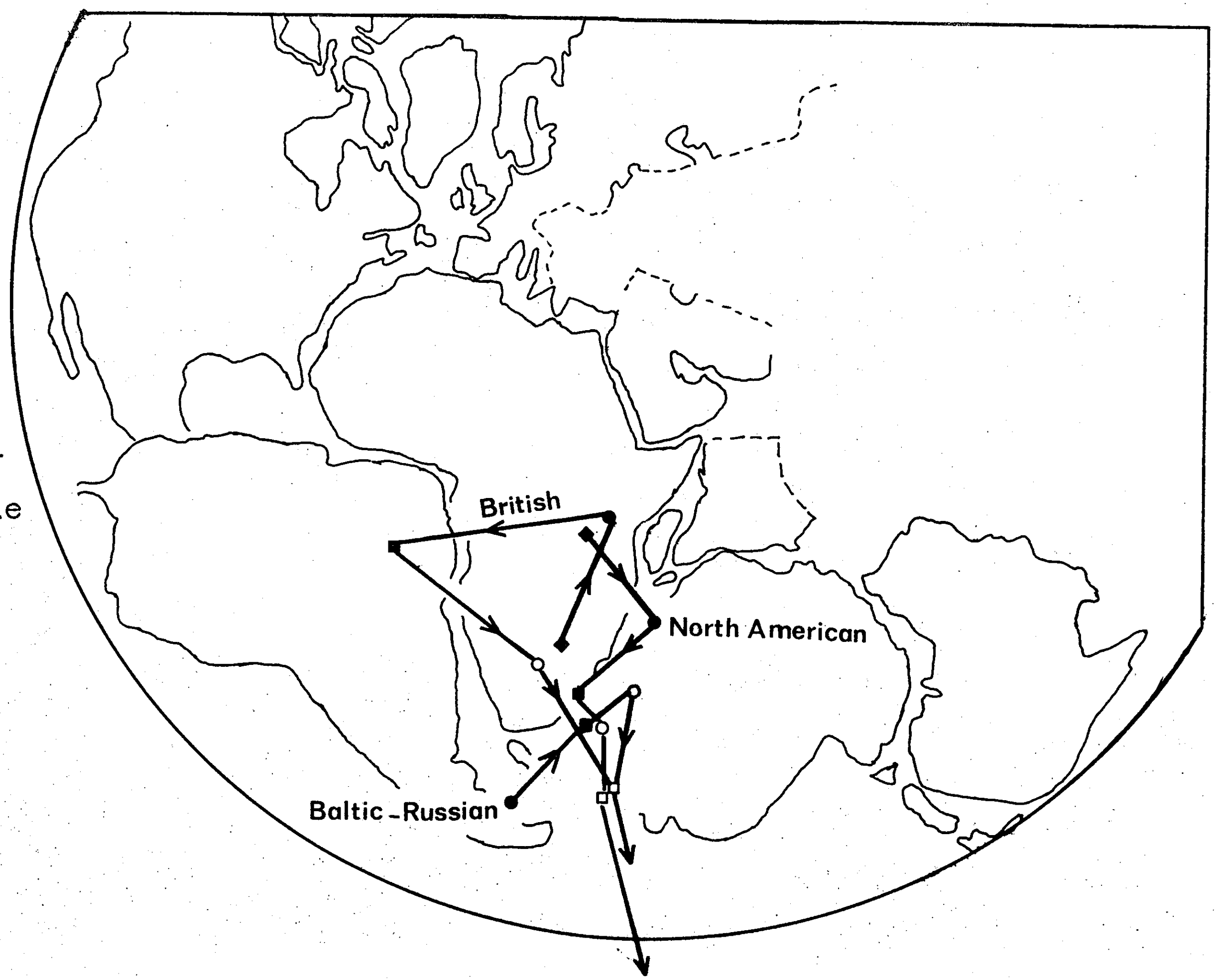
The only other results in the more westerly group are the Tortworth lavas, and the ORS sediments of the Anglo-Welsh Cuvette (CHAMALAUN and CREER 1964), this may be fortuitous. Nevertheless, in both areas there are no geological constraints to restrict postulated tectonic rotation, and the position of these studies within the Hercynian fold-belt suggests local rotations are probable.

In the Lake District (Chapter 2) it was shown that the Eycott Group and the Borrowdale Volcanic Groups have directions significantly different at the 95% level. The directional difference is purely in declination. Moseley (1960, 1964) has shown that all the sites from Ullswater, have been thrust southward on the Ullswater thrust plane. Only two sites in the overall mean calculation were collected from Kentmere where the relationship between the Borrowdale Volcanic Group and the Skiddaw Slates is unknown. A counter-clockwise rotation of 30^{o} on this thrust is inferred from the paleomagnetic data. Tectonic rotation of 'rigid' blocks has had a pronounced effect on the evolution of the Caledonides south of the Highland Boundary Fault. Insufficient information is available for the rocks north of the Fault. In many cases the present strike mapped by geologists, bears no resemblance to the actual strike of the rocks at the time of their formation. Hence to find a clear picture of the evolution of the Caledonides it is necessary to start from a position, where all rotations are reversed. Most of the reconstructions hitherto presented have failed to allowfor any tectonic rotation.

5.6 Euramerican Paleomagnetism

SMITH, BRIDEN and DREWERY (1973) have shown that during the Lower Paleozoic, the major land masses, could be divided into three distinctive regions, with distinct polar paths, namely Gondwanaland, Siberia, and Euramerica. To a first approximation these regions are regarded as single plates, although the Euramerican region is more complex and may be composed of two large plates, and at least one sub-plate. Paleozoic paleomagnetic data from America, the Baltic, and the Russian platform are sparse. Polar paths for the various parts of Europe and North America are not mutually concordant (Figure 5.8)

Figure 5.8.
The Palaeozoic polar paths from the various parts of Euramerica are distinct. Individual paths are constructed from the Geophysical Journal pole lists.



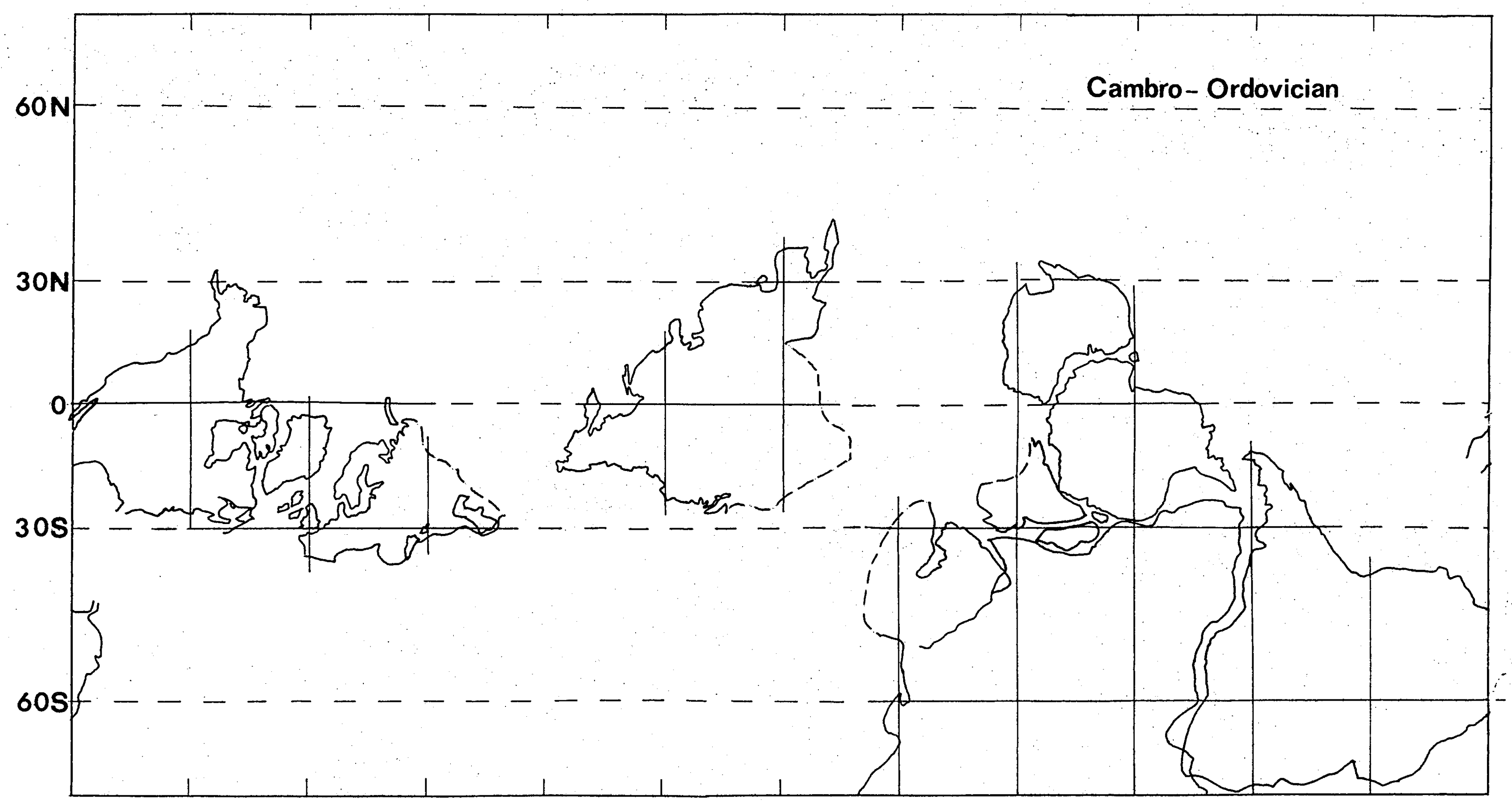


Figure 5.9. Cambro - Ordovician continent reconstruction.
Palaeo-longitude lines are at 30° intervals.

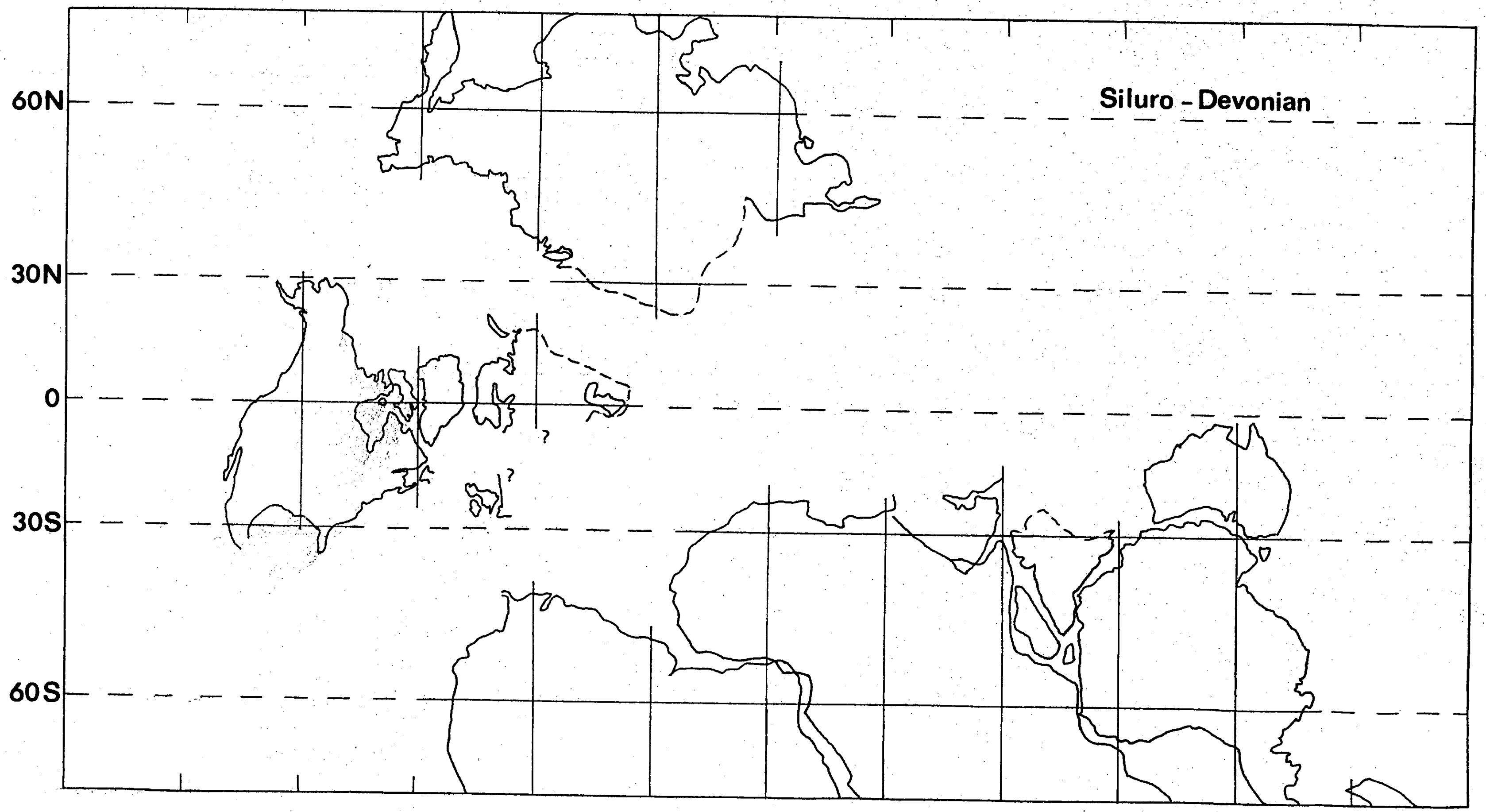


Figure 5.10. Siluro - Devonian continent distribution.
Palaeo-longitude lines are at 30° intervals.

Geometrically the simplest interpretation would be to ignore the British Cambrian and the Siluro-Devonian poles, the Russian Upper Ordovician poles, and the preliminary Cambrian pole from Norway. (POORTER 1972), the remaining data are reasonably consistent, with the poles lying in two groups. The first group includes Cambrian poles from North America, and Russia, and Ordovician poles from the British Isles. The second group contains Silurian to Permian poles from all parts of the region. On this ultra-simplified view, Euramerica would be regarded as a single plate, shifting position sometime in the late Ordovician-early Silurian. The Lower Palaeozoic world would then have had three continental groups in the approximate latitudes and orientation shown in Figures 5.9 and 5.10.

Although there is no palaeomagnetic control of relative latitude between the three continental groups, their separations cannot be drastically different from those illustrated, thus limiting the size of ocean which might have been consumed subsequently at the Urals. North Africa was close to the pole, its margin lying about 80°S beyond the southern edge of the map. Hence an ocean at least 5000 km. wide appears to have separated Euramerica from Gondwana, and it is this ocean which seems to have been consumed at the site of the Hercynides.

The existence of Paleozoic orogenic belts within Euramerica has been taken as evidence that more than one plate was involved and that large internal movements have occurred (WILSON 1966, DEWEY 1969). Moreover many of the palaeomagnetic data which have to be ignored if Euramerica is to be treated as a single plate, are better established than some of the accepted data. Using the two British Cambrian poles and the single Norwegian pole in Figure 5.9 would place the Baltic Shield 40° further North and the British Isles 20° further North. These modifications need not invalidate the concept of a Euramerican group of plates.

Taking the paleomagnetic data at their face value and overlooking those from the Urals, three dist~~rict~~inct polar paths are evident from within Euramerica - their source regions being North America, the British Isles, and the Russian Shield. The polar paths from the larger regions converge in the Silurian, the line of suture being the Scandinavian Caledonides. Tectonism there continued into the Devonian, hence plate closure predates the more spectacular evidence of orogeny.

The British Isles polar path is grossly different, and only approaches concordance with the rest of Euramerica in Devonian times. Hence, this closure is consistent neither in location nor in time with closure across the British Caledonides. Instead the loci of major closure- the principal plate margins - appear to lie entirely outside the area of the British Isles, both to the northwest beyond the Hebrides, and possibly to the east between Britain and Norway (Figure 5.11).

Data from Norway ~~is~~ are very limited and ~~non-~~ in conclusive. A single Cambrian pole (POORTER 1972) from the Fen Complex does not agree with either British, American, or Russian results. This disparity may be explained in terms of either polar shift or continental drift, but, because of the paucity of data, the possibility of Cambrian oceans is not discussed. The Sulitjelma Gabbro (PIPER in press) dated at approximately 440 my. (WILSON M.R. 1973) yields an *in situ* pole which is identical to the Aberdeenshire Gabbros. Siluro-Devonian data from Norway agree with the British Middle-Upper Devonian lower Carboniferous group (STORETVEDT *et al* 1967, STORETVEDT and GJELLESTAD 1966, Lie *et al* 1969). However of these the Ringerike sandstone has been dated as Silurian, while the Røragen sandstone is thought to be of Lower - Middle Devonian age.

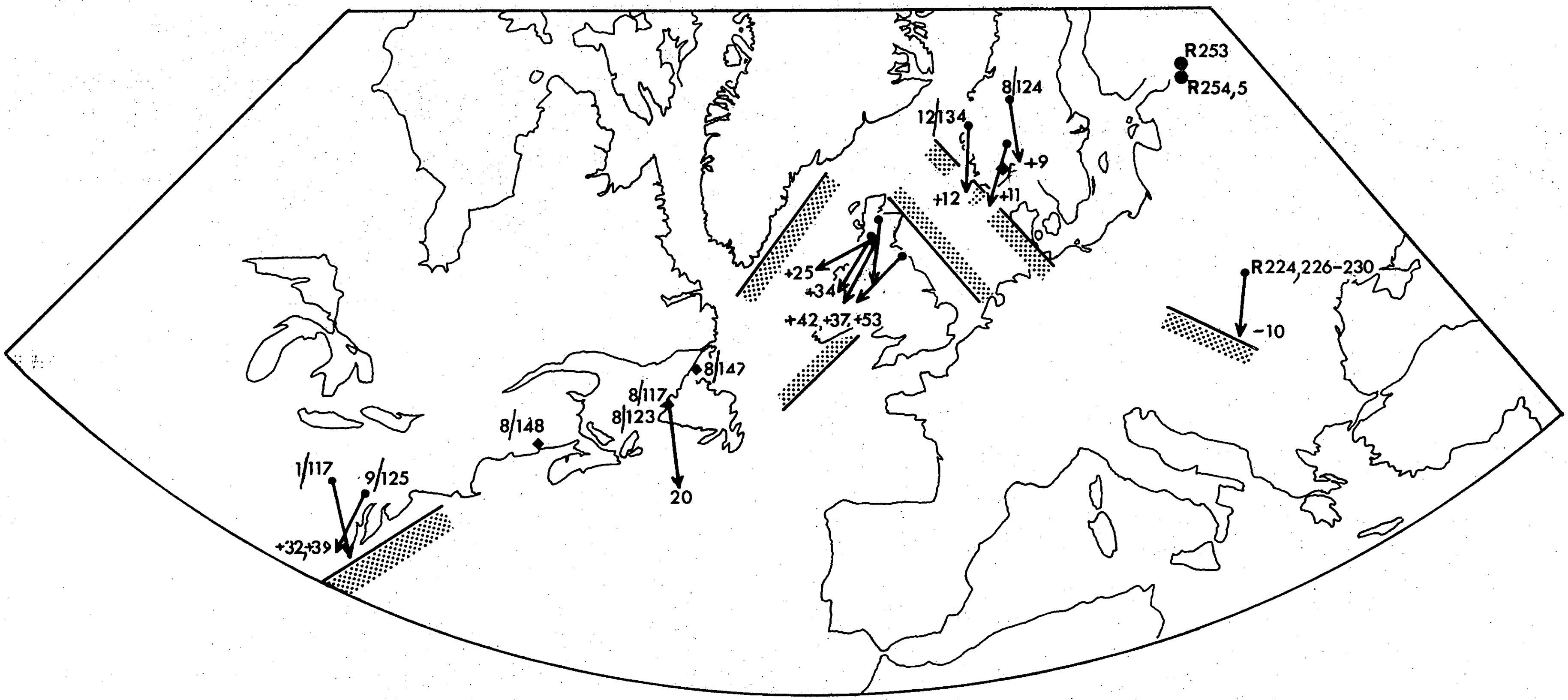


Figure 5.11. Palaeozoic plate margins within Euramerica.

Data taken from the new results presented here, the Geophysical Journal pole lists ,and McElhinny (1973).

These discrepancies can be explained in a number of ways; e.g. (a) both Norwegian and British Siluro-Devonian data are valid, implying a 25° longitude difference between the two countries during this period, (b) the Røragen and possibly the Ringerike sandstones have been incorrectly dated, (or were remagnetized in the Middle to Upper Devonian), and hence there need be no separation between Britain and Norway. The present data are ~~non-~~inconclusive, and more data ~~is~~ are urgently required from all parts of the Scandinavian Caledonides.

5.7 Paleozoic plate margins within Euramerica

If major orogenic belts are to be identified as the sites of pre-existing plate margins then the two principal plate margins within Europe and North America were along the Caledonides and the Hercynides Palaeomagnetic evidence for closure across the Caledonides has been reviewed in Section 5.3. Assessment of closure across the Hercynides is inhibited by two factors - the indeterminacy of relative longitude which is inherent to the palaeomagnetic method, and the complete absence of pre-Carboniferous data from Europe south of the northern margin of the Hercynide belt.

Fortunately, the difference in Cambro-Ordovician latitudes between northern Europe and North Africa (the 'forelands' of the Hercynides) is so great that a minimum of 5000 km. of ocean is inferred to have lain between them in early Paleozoic times.

In the previous Section two further margins were proposed on palaeomagnetic grounds alone. Geological evidence for a suture between Scotland and Greenland is sparse, mainly because it is based on purely distributional arguments. Reconstructions of a North Atlantic Archean craton, have shown that correlation between Greenland and Labrador is quite straight forward, whereas correlations between Greenland and Scotland are not as simple (BRIDGEWATER et al. 1973). The presence of the Laxfordian belt inhibiting direct correlation. It was shown in Section 5.5 that tectonic rotation of western Eire probably took place in the early Devonian. Reversing this rotation brought all palaeomagnetic data from the Mayo Trough into agreement with other British data. KENNEDY et al. (1972) have shown the Leck-Leenaun fault (PITCHER et al. 1964), and its proposed extension in Newfoundland (WILSON 1962) cross-cut one another. Applying the rotation correction brings the two faults into parallelism, but not alignment. These remaining discrepancies are not sufficient to explain the major differences recorded by the palaeomagnetic data. Further new data ~~is~~ are required especially from Scotland and America.

Although the palaeomagnetic data ~~is~~ are less conclusive, there is a variety of geological evidence for a major tectonic boundary in or around the present North Sea region. The Lower Paleozoic rocks of eastern England consist of strongly folded arenaceous and argillaceous sediments with minor calcalkaline intrusions, and similar rocks may extend southwards into Belgium (Le Bas 1972). Folded Paleozoic basement was recognised beneath the north German Lowlands as long ago as 1880 (TORNQUIST 1908, quoted by DORN 1960, STILLE 1925). The structural trend of these rocks in eastern England is NNW-SSE (CHARNOID) contrasting with the typical NE-SW (CALEDONOID trend) of Paleozoic structures in Scotland. BAILEY (1928) and TURNER (1949) recognised a western boundary of folded Lower Paleozoics in the east Midlands of England. Turner traced this boundary and the parallel Charnoid structures northwards into northern England where they gradually swing into parallelism with the Caledonoid trend.

A plate margin of Charnoid trend would inevitably intersect the Caledonide plate margin in a triple junction. Unless the relative velocities of the three plates meeting at the triple junction satisfied special conditions for stability, then the junction would itself migrate with time (McKENZIE and MORGAN 1969). Perhaps this explains the difficulty of locating a plate margin west of the triple junction, which could have occupied various sites at various times, along a variety of NE-SW lines from the Southern Uplands northwards.

The palaeomagnetic evidence relating to these two postulated margins are independent of each other. The existence of a 'North Atlantic' plate margin is purely dependent upon major disagreements between British and American data. While the 'North Sea' plate margin although geologically well-founded has little paleomagnetic support. The existence of a plate margin in the North Sea would help explain the lack of continuity in structural style and the evolution on the south-east margin of the Caledonides between Norway and Scotland. Nevertheless, it should be emphasised that the bulk of tectonic, palaeontologic and sedimentologic evidence all points to the site of the Caledonides as the principal seaway within Euramerica rather than the lines postulated here. Further palaeomagnetic investigations are urgently required. Studies of Ordovician and Siluro-Devonian rocks from northern Europe and North America would confirm (or invalidate) the proposed individuality of the British Isles sub-plate. Additionally late Pre-Cambrian and Cambrian data from all regions could help determine the convergence history of the Caledonide belt.

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TABLE 1.1.

SYMBOLS AND ABBREVIATIONS

ARM	Anhysteritic Remanent Magnetization
CRM	Chemical Remanent Magnetization
D	Declination of Magnetic Vector
I	Inclination of Magnetic Vector - positive downwards
IRM	Isothermal Remanent Magnetization
χ	Volume Susceptibility
M	Moment of remanent magnetization vector
M_o	Initial moment of remanent magnetization vector (M_{NRM})
NRM	Natural Remanent Magnetization
O_e	Oersted(s)
Q_n	Koenigsberger ratio of NRM
S.I.	Stability Index
TRM	Thermoremanent Magnetization
VRM	Viscous Remanent Magnetization
RRM	Rotational Remanent Magnetization.
N	Number of speciments or sites (dependent upon level)
R	Resultant Vector
k	Fisher's precision parameter
$\alpha 95$	Semi-angle of the cone of 95% confidence about the mean direction
Lat.	Palaeomagnetic pole latitude (positive N of the equator).
Long.	Palaeomagnetic pole longitude (E of Greenwich).
$d\psi$ $d\chi$	Semi-axes of the oval of confidence about the palaeomagnetic pole

TABLE 2.1

The Eycott Group - Binsey Formation

Total NRM

Site	Location °N	Location °W	N	R	k	α95	in situ D	in situ I	dip corrected* D	dip corrected* I
25	54.7	3.2	6	4.85	4.3	36	0	+24	355	-42
26			5	4.95	80.9	8	16	+5	11	-59
27			6	3.37	not significant					
28			6	5.51	10.1	22	13	+16	8	-53
29			6	4.68	3.8	40	5	+19	359	-48
30			6	5.86	36.3	11	15	+44	16	-25
31			6	5.91	55.5	9	16	+23	15	-47
32			7	5.43	38.1	36	301	+82	13	+19
33			6	4.48	3.3	44	5	+17	357	-50
34			5	4.95	79.7	8	24	+32	24	-38
1	54.6	3.0	6	5.66	14.9	18	13	+44	26	+13
2			6	5.89	44.8	10	42	-4	37	-41
3			6	3.32	not significant					
4			4	3.31	4.4	50	26	-25	5	-55
5			6	3.34	not significant					

* Dip correction by simple rotation about strike

TABLE 2.2

The Eycott Group - Binsey Formation

a. f. cleaned

Site	Peak Field	N	R	k	α_{95}	in situ D	in situ I	dip corrected* D	dip corrected* I	Virtual Geomagnetic Pole °E	Virtual Geomagnetic Pole °N
25	200	6	5.92	62.0	9	3	-17	356	-45	181	+9
26	200	6	5.98	271.0	4	10	+ 9	352	-63	183	-9
27	200	5	4.47	8.0	30	357	+17	347	-46	189	+7
28	300	6	5.78	22.9	14	13	+14	359	-58	178	-4
29	200	6	5.93	72.5	8	3	+12	350	-54	185	+1
30	700	5	4.83	23.9	16	19	+20	19	-50	101	+3
31	500	6	5.92	61.9	9	16	+12	12	-58	168	-4
32	700	5	4.92	47.0	11	25	+26	26	-44	154	+6
33	700	6	5.94	304.0	4	21	+26	21	-44	158	+7
34	700	5	4.92	47.4	11	26	+30	26	-39	152	+10
1	500	6	5.82	28.8	13	20	+14	13	-25	163	+21
2	200	6	5.98	222.0	5	27	-32	358	-61	179	-6
3	900	6	5.44	9.0	24	355	-33	325	-43	209	+5
4	300	3	2.89	18.8	29	24	-20	6	-49	172	+5
5	700	6	2.76	not significant							

* Dip correction by simple rotation about strike.

TABLE 2.3

The Eycott Group - High Ireby Formation.

Total NRM

Site	Location °N	Location °W	N (samples)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected*)	I (dip corrected*)
6	54.6	3.0	6	4.42	3.2	45	78	+13	78	-20
7			6	2.96	not significant					
8			6	2.94	not significant					
9			6	5.19	6.2	29	34	+16	34	-19
10			7	6.20	7.5	24	13	-11	0	-37
11			6	5.44	8.9	24	10	-22	348	-44
12			6	5.77	21.4	15	51	+12	51	-26
13			6	5.86	35.9	11	40	+57	47	-20
14			6	3.88	2.4	56	11	-16	353	-42
15			6	5.44	8.9	24	42	+5	40	-32
20	54.7	3.2	6	5.67	15.3	18	351	+43	358	-21
21			6	5.33	7.3	26	355	+36	358	-29
22			6	3.98	2.5	54	346	+34	349	-26
23			5	2.54						
24			5	2.88						
40	54.7	3.0	6	5.96	110.0	6	358	+36	5	-11
41	54.7	3.0	6	5.80	24.4	14	14	36	19	-14

* Dip correction by simple rotation about strike.

TABLE 2.4

The Eycott Group - High Ireby Formation.

a.f. cleaned

Site	Peak Field	N	R	k	α_{95}	in situ D	in situ I	dip corrected* D	dip corrected* I	Virtual Geomagneti Pole °E	Virtual Geomagneti Pole °N
6	600	5	4.07	4.3	42	27	-32	358	-61	179	-7
7	600	5	4.09	4.4	41	40	-12	21	-47	159	+6
8	600	4	3.92	36.8	15	2	-18	344	-37	192	+14
9	700	5	4.42	6.9	31	30	-30	5	-61	174	-6
10	700	5	4.83	23.1	16	12	-10	0	-35	178	+16
11	100	6	5.86	36.7	11	9	-21	347	-42	189	+10
12	700	6	5.87	39.2	11	5	-17	347	-37	190	+14
13	700	6	5.88	43.0	10	17	+3	12	-26	165	+21
14	800	5	4.88	34.0	13	10	-17	353	-40	184	+13
15	800	5	4.83	24.2	16	14	-22	356	-44	180	+10
20	500	6	5.59	12.2	20	358	+31	356	-35	181	+16
21	200	5	4.95	94.0	8	356	+18	352	-38	185	+13
22	200	6	5.96	130.0	6	349	+34	352	-38	186	+20
23	700	5	2.62	not significant							
24	700	4	2.33	not significant							
40	200	6	5.98	248.0	4	352	+38	360	-11	178	+30
41	200	6	5.96	115.0	6	5	+41	10	-12	166	+29

TABLE 2.5

The Eycott Group

							Palaeomagnetic pole			
Binsey Formation	N	R	k	α_{95}	D	I	$^{\circ}E$	$^{\circ}N$	$d\psi$	$d\chi$
NRM *in situ*	12	10.59	7.8	16	15	+23	155	46	9	18
NRM Dip corrected*	12	10.80	9.1	15	13	-37	164	14	10	18
a.f. cleaned *in situ*	14	12.89	11.7	12	14	+6	159	37	6	12
a.f. Dip corrected*	14	13.55	28.7	8	5	-50	173	5	7	10
High Ireby Formation										
NRM *in situ*	13	9.90	5.2	21	19	+21	150	44	11	22
NRM Dip corrected*	13	11.67	9.1	15	19	-28	158	18	9	16
a.f. cleaned *in situ*	15	13.19	7.7	15	10	-2	165	34	7	15
a.f. cleaned dip corrected*	15	14.44	25.0	8	358	-37	179	15	5	9
Combined										
NRM *in situ*	25	21.42	6.7	12	18	+22	152	44	7	13
NRM Dip corrected*	25	22.12	8.3	11	16	-31	161	17	7	12
a.f. cleaned in situ	29	26.03	9.4	9	12	+2	162	35	5	9
a.f. cleaned Dip corrected*	29	27.51	22.3	6	0	-43	175	10	5	7

*Tilt correction by simple rotation about the present strike.

TABLE 2.6

The Borrowdale Volcanic Group.

Total NRM - Site mean statistics.

Site	N	R	k	α95	D	I	D	I
	(samples)				(in situ)		(dip corrected)	
4	7	6.92	78.5	7	313	-65	326	+2
5	6	4.11	2.4	52	323	+47	2	+33
6	5	3.88	3.6	47	38	-1	30	-44
7	7	5.20	3.3	39	345	-18	326	-26
8	5	1.52	not significant					
9	5	4.88	34.4	13	309	+62	217	+72
10	6	4.66	3.7	40	308	-12	307	+18
11	7	6.63	16.3	15	352	+72	151	+73
67	6	2.31	not significant					
68	5	2.64	not significant					
69	5	4.87	29.8	14	188	-82	123	-63
70	7	6.76	24.5	12	119	-54	115	-29
71	6	5.46	9.3	23	269	+81	285	+57
72	6	4.13	2.7	51	63	+80	315	+70
73	7	5.40	3.8	36	262	-39	246	-61
74	7	5.99	6.0	27	353	+23	355	-5
75	5	3.63	2.9	55	70	-41	76	-56
76	6	5.95	94.6	7	254	-69	311	-56
77	7	6.93	85.9	7	267	-80	332	-58
78	5	4.33	5.9	34	156	-76	3	-74

TABLE 2.6 (continued)

The Borrowdale Volcanic Group.

Total NRM - Site mean statistics.

Site	N	R	k	α_{95}	D	I	D	I
	(samples)				(in situ)		(dip corrected)	
79	7	6.93	74.1	7	292	-79	334	-53
80	6	5.29	7.0	27	355	-57	350	-27
81	6	5.46	9.3	23	307	-10	306	-20
82	5	4.71	13.6	22	310	-88	141	-67
84	6	5.20	6.3	29	288	+62	255	+49

TABLE 2.7

The Borrowdale Volcanic Group

a.f. cleaned - site mean statistics.

Site	Optimum Field	N (samples)	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
PRINCIPAL GROUP									
4	100	7	6.92	75.1	7	313	-66	330	-29
5	300	6	1.83	not significant					
6	500	5	4.76	16.7	19	11	-17	349	-43
7	300	6	5.86	36.8	11	9	-26	337	-48
8	500	5	4.91	43.4	12	19	-1	357	-23
10	400	6	5.97	145.1	6	275	-74	320	-46
74	200	7	6.38	9.6	21	348	-6	343	-33
75	200	5		not significant					
76	200	5	4.95	87.6	8	259	-69	312	-54
77	200	6	5.95	98.2	7	241	-82	332	-62
78	200	5	4.37	6.3	33	146	-81	3	-74
79	200	6	5.94	117.0	6	311	-81	340	-53
80	100	6	5.36	7.9	26	359	-60	355	-30
81	200	6	5.77	21.5	15	322	-37	322	-47

TABLE 2.7 (continued)

The Borrowdale Volcanic Group

a.f. cleaned - site mean statistics.

Site	Optimum field	N (samples)	R	k	$\alpha 95$	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
ANOMALOUS GROUP									
9	300	6	5.79	24.3	14	316	+53	248	+75
11	200	5	4.65	11.4	24	355	+70	146	+74
67)) 68)	unstable upon a.f. demagnetisation								
69	200	5	4.90	38.0	13	193	-82	125	-63
70	200	6	5.79	23.3	14	118	-56	114	-31
71	200	6	4.36	3.0	46	155	+73	248	+73
72	500	6	2.23	not significant					
73	200	6	5.58	12.0	20	249	-57	203	-71
82	200	6	5.70	16.7	17	248	-90	142	-65
84	300	5	4.71	13.6	22	284	+75	238	+58

TABLE 2.8

The Borrowdale Volcanic Group

Overall analysis

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							(Palaeomagnetic Pole).			
PRINCIPAL GROUP										
NRM										
in situ	13	8.07	2.4	34	340	-46	6°N	195°E	28	44
dip corrected	13	9.94	3.9	24	340	-33	16°N	197°E	16	27
a.f. cleaned										
in situ	12	9.58	4.5	23	345	-57	3°S	189°E	25	34
dip corrected	12	11.46	20.3	10	338	-46	6°N	196°E	8	13
ANOMALOUS GROUP (allowing for dual polarity).										
NRM										
in situ	9	8.24	10.6	17	337	+80	71°N	334°E		
dip corrected	9	8.03	8.3	19	288	+72	51°N	300°E		
A.f. cleaned										
in situ	8	7.43	12.3	16	337	+80	71°N	334°E	30	32
dip corrected	8	7.31	10.2	18	284	+73	50°N	305°E	29	33

TABLE 2.9

Diabase Dyke - Stile End

Total NRM - site mean analysis

Site	N (samples)	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
1	7	6.16	7.2	24	95	+56	125	+34
2	6	5.78	22.5	15	205	+28	191	+9
3	6	4.95	4.8	34	75	+64	126	+47

a.f. cleaned - site mean analysis

Site	Optimum field	N (sample)	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
1	500	6	5.09	5.5	31	94	-68	23	-55
2	700	6	5.21	6.4	29	14	-83	351	-48
3	300	5	3.50	not significant					

TABLE 2.10

Diabase Dyke - Stile End

Overall analysis

	N (samples)	R	k	$\alpha 95$	D	I	Lat. (Palaeomagnetic Pole)	Long.	$d\psi$	$d\chi$
NRM										
in situ	20	15.01	3.7	20	137	+68	22°N	25°E	29	34
dip corrected	20	15.14	3.9	19	154	+33	14°S	23E	12	22
A.f. cleaned										
in situ	12	10.12	5.9	20	76	-78	44°S	145°E	35	37
dip corrected	12	10.13	5.9	20	5	-53	2°N	173°E	19	27

TABLE 2.11

Carrock Fell Gabbro Complex

Total NRM - site mean analysis

Site	Location °N	Location °W	N	R	k	α95	D (in situ)	I (in situ)
2	54.7	3.1	6	3.00	not significant			
4			5	4.62	10.6	25	291	+32
5			6	5.21	6.3	29	6	+33
6			4	3.80	14.8	25	311	+73
10			6	4.65	3.7	40	44	+72
11			6	5.67	15.0	18	191	+10
12			6	4.28	2.9	48	119	+81
13			7	5.07	3.1	41	192	-10
14			5	1.41	not significant			
15			6	5.54	10.9	21	346	-2
16			6	4.67	3.8	40	193	-30
17			6	3.30	not significant			
18			4	2.52	not significant			
19			5	2.41	not significant			
21			6	5.78	22.8	14	23	-33
22			6	4.16	2.7	50	16	-10
23			5	4.99	448.6	4	349	-9
24			4	1.88	not significant			
30			6	5.65	14.2	18	287	+62

TABLE 2.11 (continued)

Carrock Fell Gabbro Complex

Total NRM - site mean analysis

Site Location °N	°W	N	R	k	α95	D (in situ)	I (in situ)
31		6	0.73	not significant			
32		6	5,25	6.7	28	163	+57
50		6	4,77	4.0	38	2	-13
51		6	3.49	not significant			
52		6	2.66	not significant			
53		5	4.61	10.3	25	348	+51
54		3	1.06	not significant			
55		7	6,46	11.1	19	275	+65
56		6	5.22	6.4	29	352	+29
57		4	1,08	not significant			
60		6	2.95	not significant			

TABLE 2.12

Carrock Fell Gabbro Complex

a.f. cleaned - site mean analysis

Site	Optimum field	N	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected*)	I (dip corrected*)
2	300	6	3,51	not significant					
4	700	6	5.31	7,3	27	345	-49	333	-52
5	400	6	5,46	9,3	23	4	-1	3	-7
15	200	6	5,13	5,8	31	338	-21	334	-23
16	300	6	5,50	10,0	22	351	-30	347	-34
17	200	7	5,46	3.9	35	323	-22	319	-21
18	400	6	5,84	30.3	12	351	-23	347	-27
19	200	5	2,14	not significant					
21	500	6	5,63	13.3	19	7	-35	1	-41
22	400	6	5,89	46,0	10	8	-15	5	-21
23	200	5	4,99	435.5	4	350	-14	348	-18
24	300	4	3,90	30,9	17	347	-25	347	-28
30	500	5	4.88	33,8	14	343	+8	344	+5
31	700	6	3.12	not significant					
50	300	6	5.51	10.1	22	354	-25	349	-30
51	300	6	5,85	32,2	12	6	-26	1	-32
52	300	6	4,68	3,7	40	0	+28	3	+22
53	300	5	4.36	6.3	33	348	+12	350	+8
54	300	3	0,67	not significant					
55	300	7	5,98	5.9	27	337	+11	339	+9
56	200	5	4.97	114,9	7	354	-4	351	-18

*tilt corrected for overlying Carboniferous

TABLE 2.13

Carrock Fell Gabbro Complex

a.f. cleaned - Overall analysis

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							(Palaeomagnetic Pole)			
in situ	17	15.77	13.1	10	351	-15	27°N	187°E	5	11
dip corrected for arboniferous	17	15.78	13.1	10	349	-19	25°N	189°E	6	11
dip corrected to produce vertical mineral lamination	17	15.76	12.9	10	351	-29	19°N	184°E	6	11

TABLE 2.14

Diabase dykes intruding Eycott Group

Total NRM

Site	Location °N	°W	N	R	k	α95	(in situ) D	I	(dip corrected) D	I
61	54.6	2.9	6	5.07	5.4	32	302	+85	28	+81
62			7	6.86	41.9	9	358	+52	7	+46
63			7	6.66	17.6	15	14	+77	32	+69
64			4	3.61	7.8	35	20	+82	39	+73
65			5	4.91	42.8	12	38	+70	44	+61
66			7	6.78	27.3	12	50	+73	52	+63
mean of six sites				5.85	32.7	12	17	+75	32	+66

a.f. cleaned

Site	Peak field	N	R	k	α95	(in situ) D	I	dip corrected D	I	Paleomagnetic Pole °E	°N
61	200	6	5.89	46.6	10	357	+51	6	+45	166	+62
62	100	7	6.95	119.6	6	353	+50	2	+45	174	+62
63	300	6	5.87	38.6	10	24	+73	35	+64	94	+66
64	300	4	3.68	9.2	32	85	+72	75	+63	67	+43
65	300	6	5.99	327.3	4	19	+66	29	+57	116	+64
66	300	6	5.99	497.2	3	21	+70	32	+62	106	+66
mean of six sites			5.80	24.6	14	14	+66	25	+58	120	+67

TABLE 2.15

The Cockermouth Lavas

Total NRM - site mean analysis

Site	N (samples)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
5	5	3.73	3.2	52	90	+17	90	+25
1	6	5.82	28.8	13	73	-40	97	-13
3	6	5.17	6.0	30	345	+50	338	+46
2	6	4.38	3.1	46	316	+26	317	+27
4	7	5.15	3.3	40	319	-32	322	-24

a.f. cleaned - site mean analysis

Site	Peak field	N (samples)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
5	200	5	4.70	13.1	22	114	-15	114	-7
1	200	6	5.77	21.5	15	96	-27	96	-19
combined		11	10.29	14.0	13	104	-22	104	-14
3	500	5	4.88	34.2	13	5	-20	8	-20
2	700	5	4.21	5.1	38	30	-31	34	-27
combined		10	8.88	8.0	18	16	-26	19	-24
4	200	6	5.34	7.6	26	288	-43	299	-49

sites are arranged in stratigraphic order

TABLE 3.1

S.E. Connemara Series - Gorumna

Site mean statistics - NRM

Site	N (specs)	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
1	6	5,87	38.8	11	343	+80	359	-15
2	6	4,33	3,0	47	293	-4	286	-3
3	6	4.12	2,7	51	185	-27	144	+77
4	5	3.47	2.6	not significant				
5	6	5.49	85,3	7	214	+84	14	-15
6	6	4,29	2,9	48	233	-3	5	+64
7	6	4.47	3,3	44	167	+42	174	0
8	6	5.82	28.2	13	183	+38	1	+7
9	7	5.15	3,3	40	08	+45	307	-41
10	4	2,73	2.4	not significant				
11	7	0,82	0,9	not significant				
12	6	5,93	77,4	8	63	+86	18	-34

TABLE 3.2

S.E. Connemara Series - Gorumna

Overall analysis - NRM

	N	R	k	α_{95}	D	I	Palaeomagnetic Pole Position Lat	Long	$d\psi$	$d\chi$
all significant sites										
in situ	9 (sites)	5.34	2.2	47	230	+54	9°N	311°E	47	66
dip corrected	9	5.72	2.4	42	353	+3	38°N	179°E	21	42
All sites significant at 99% level (Watson 1959b)										
in situ	24 (samples)	21,56	9,4	10	187	+80	33°N	347°E	19	19
dip corrected	24	22.65	18,9	7	8	-14	29°N	162°E	11	22

TABLE 3.3

S.E. Connemara Series - Gorumna

Site mean statistics - A.F. cleaned

Site	Optimum field	N (specs)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
1	500	5	4,66	11,6	24	329	+86	1	-8
2	400	6	3,60	2.1	not significant				
3	300	6	4.47	3.3	44	206	-31	230	+76
4	400	5	2,40	1,5	not significant				
5	300	6	5,89	49,7	10	281	86	12	-20
6	300	6	2.68	1.5	not significant				
7	100	6	4,66	3.7	40	174	+23	23	+28
8	300	6	5.38	8.1	25	175	-8	11	+52
9	300	6	4,58	3.5	42	308	+50	324	-39
10	700	4	1,70	1,3	not significant				
11	300	7	1,00	1,0	not significant				
12	400	6	5,29	7,1	27	155	77	23	-20

TABLE 3.3 (continued)

S.E. Connemara Series - Gorumna

Overall analysis - A.f. cleaned

	N	R	k	α_{95}	D	I	Lat.	Long	$d\psi$	$d\chi$
							(palaeomagnetic pole)			
All significant sites										
<u>in situ</u>	6	4.31	2.2	53	196	+54	1°S	337°E	53	75
dip corrected	6	4.76	2.7	46	5	+9	42°N	164°E	24	47
Four best grouped sites										
<u>in situ</u>	23	19.38	6.1	13	293	+83	57°N	325°E	26	26
dip corrected	23 (samples)	19.00	5.5	14	4	-23	24°N	168°E	17	33

TABLE 3.4

Arenig pillow lavas - Lough Nafooey

Site mean analysis - NRM

Site	N (specs)	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
1	8	7.82	38.5	9	30	+74	348	+10
2	8	6.52	4.7	29	222	+75	315	+14
3	11	9.46	6.5	19	257	+88	345	+10
4	9	5.52	2.3	44	201	+37	260	+72
34	5	4.76	16.8	19	139	+66	349	+33
44	6	5.59	12.3	20	64	+80	16	+74
45	5	4.91	42.4	12	347	+78	342	+66
46	6	3.14	not significant					
47	6	5.07	5.4	32	11	+81	3	+43
48	6	5.48	9.5	23	196	+68	33	+35
49	6	5.48	9.6	23	160	+76	340	+25
50	5	4.93	54.8	10	119	+73	352	+22
51	5	3.41	not significant					
52	5	2.43	not significant					
53	6	5.20	6.2	29	238	+13	253	+18
54	6	5.98	268.2	4	329	+77	10	-8
55	6	3.57	not significant					
56	6	5.32	7.4	27	82	+27	74	-13
57	6	5.91	55.1	9	328	+78	11	-8
58	5	4.66	11.9	23	76	+42	21	+15
66	5	2.78	not significant					

TABLE 3.5

Arenig pillow lavas - Lough Nafooey

Site mean analysis - A.f. cleaned

Site	Optimum field	N (specs)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
1	300	7	6,96	142,7	5	2	+77	345	-2
2	300	7	6.58	14,4	16	194	+ 2	213	+35
3	300	6	4.02	2.5	54	191	+60	321	+26
4	300	5	4,78	17,8	19	173	-14	174	+ 35
34	300	5	4,10	4,5	41	139	+56	357	+ 43
44	500	4	2.54	not significant					
45	200	unstable upon a.f. demagnetisation							
46	400	5	4,52	8,3	28	204	-40	203	-1
47	500	4	3.53	6,5	39	354	+49	350	+11
48	300	6	5.47	9,3	23	208	+43	33	+52
49	500	5	4.86	28,1	15	216	+74	326	+19
50	700	5	4.72	14,0	21	181	+75	334	+24
51	500	5	2.35	not significant					
52	300	4	0.84	not significant					
53	300	5	4,05	37,9	13	227	-12	226	+ 9
54	300	7	6,34	10,2	20	276	+55	345	+ 8
55	200	6	2,89	not significant					
56	300	6	5.74	19,1	16	89	+72	38	+12
57	500	6	5.85	34,3	12	333	+69	5	-14
58	500	4	3.70	10,1	30	86	+ 46	25	+18
66	500	5	2.64	not significant					

TABLE 3.6

ARENIG PILLOW LAVAS - LOUGH NAFOOEY

Overall analysis

	N (sites)	R	k	α_{95}	D	I	Lat.	Long	$d\psi$	$d\chi$
							Palaeomagnetic pole			
NRM										
in situ	16	13.60	6.3	16	145	+84	43°N	0°E	31	32
dip corrected	16	11.77	3.6	23	355	+31	53°N	179°E	14	26
A.F. cleaned										
in situ	15	9.36	2.5	31	195	+64	9°N	339°E	39	49
dip corrected	15	6.62	1.9	40	339	+35	53°N	204°E	26	46
A.F. cleaned (allowing for dual polarity)										
in situ	15	10.88	3.4	25	24	+75	74°N	35°E	41	45
dip corrected	15	12.45	5.5	18	4	+10	42°N	165°E	9	18

TABLE 5.7

Mweelrea ignimbrites - Site data

		Total NRM							a.f. cleaned							
Ignimbrite band	Site	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)	Peak field	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
1	7	4	3.99	623.0	131	-27	132	+23	200	3	2.99	677.7	131	-33	135	+17
	11	6	5.64	13.9	127	+48	136	-13	500	6	5.29	7.0	112	+42	123	-13
	13	10	8.13	4.8	146	+9	131	+61	300	6	5.65	14.1	174	-4	181	+49
	35	6	4.59	3.6	156	+21	156	-29	400	7	5.73	4.7	132	+25	133	-21
	37	6	5.94	80.0	350	-17	350	-5	200	6	5.33	7.5	41	-10	40	-4
	38	6	5.27	6.8	61	+47	74	+48	300	7	6.82	33.5	75	+27	81	+26
	43	6	3.32	not significant					200?	5	3.50	not significant				
2	14	9	5.19	2.1	129	+1	113	+44	300	7	5.81	7.6	146	-18	148	+27
	36	6	5.40	8.4	305	+75	166	+53	500	7	6.66	17.6	348	+71	145	+59
3	15	4	3.70	10.1	173	+80	337	+45	600	4	3.83	117.7	186	+83	336	+41
	16	9	7.90	7.3	337	+74	339	+35	800	6	5.44	8.9	166	+87	350	+49
	20	7	5.38	3.7	181	-14	199	+47	800	5	4.68	7.5	227	+63	306	+42
	40	6	5.06	5.3	304	+23	311	0	200	4	3.16	3.6	306	+6	303	-15
	41	5	3.07	not significant					200	4	3.50	6.0	355	-10	352	-47
	42	6	1.68	not significant					300	4	3.28	4.2	262	+12	269	+17

TABLE 3.7 (continued)

Mweelrea ignimbrites - Site data

		Total NRM								a.f. cleaned						
Ignimbrite band	Site	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)	Peak field	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
4	6	3	2.99	1616.0	141	-12	136	+40	700	3	2.99	1125.6	141	-17	138	+35
	8	10	9.95	194.0	117	+52	138	+7	200	7	6.98	237.7	115	+51	136	+6
	10	10	9.67	27.1	120	+70	141	+36	200	7	6.98	241.1	128	+57	144	+22
	12	9	8.97	294.8	34	+68	133	+45	200	6	5.99	603.1	62	+70	133	+34
	17	9	5.68	2.4	120	-47	133	-10	200	7	3.48	not significant				
	21	12	11.03	11.3	129	-15	126	+39	200	8	7.70	23.1	141	-22	140	+33
	39	6	4.32	3.0	105	+7	121	+44	200	6	4.38	3.1	136	-11	135	+15
5	9	10	8.87	8.0	319	+84	160	+36	300	7	6.71	20.3	65	+63	126	+27
	18	5	4.07	4.3	170	+17	160	+55	200	7	5.54	4.1	170	+15	167	+31
	22	6	1.45	not significant					200	6	5.51	10.2	125	+12	105	+63

TABLE 3.8

Mweelrea Ignimbrites - Fold tests and overall analysis

BAND	N	R (in situ)	k	R dip corrected	k	D	I	virtual geomagnetic pole Long.	Lat.	$d\psi$	$d\chi$	Significance of fold test
1	6 sites	3,96	2.5	4,11	2,6	114	+12	58°E	9°S	27	52	not significant
	35 specs	21.31	2,5	21.41	2.5	110	+12	60°E	7°S	10	20	low precision
2	2 sites	insufficient for analysis										
	13 specs	9,15	1.5	11.57	8.4	147	+45	20°E	5°S	12	19	significant at 99% level
3	6 sites	3,67	2,1	4.18	2,8	318	+18	315°E	19°N	27	52	
	32 specs	17.45	2,1	19.75	2.5	315	+19	226°E	33°N	11	21	not significant low precision.
4	6 sites	4,45	3,2	5,89	45.0	137	+24	33°E	14°S	6	11	
	37 specs	26.05	3.3	34.31	14.0	138	+24	33E	15°S	4	7	significant at 99% level
5	3 sites	insufficient for analysis										
	20 specs	18.09	2.6	16.28	5.1	136	+43	29°E	3°S	12	20	significant at 95% level
All sites	23 sites	10,29	1.8	11.49	1.9	128	+41	36°E	1°S	23	38	
	5 bands	3,25	non-significant									
Bands 1,2,4,5	17 sites	11.29	2.8	14,17	5,6	131	+27	38°E	11°S	10	18	significant at 95% level
	4 bands	3,83	17,9	3,84	18,6	133	+30	36°E	10°S	13	24	not strictly applicable

TABLE 3.9

Derry Bay Felsite

Site mean analysis - Total NRM

Site	N (specs)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
28	5	4,90	38,2	13	199	+36	208	+46
29	3	2,92	23,5	26	202	+42	212	+52
30	6	3,97	2,5	55	213	+62	244	+67
31	6	5.67	15,3	18	167	+74	240	+87
32	5	4.66	11,7	25	175	+63	188	+74
33	6	5.52	10,3	22	117	+68	88	+75

Site mean analysis - A.F. cleaned

Site	Optimum field	N (specs)	R	k	α95	D (in situ)	I (in situ)	D dip corrected	I dip corrected
28	300	5	4,88	33,3	14	194	-9	194	+3
29	300	5	4,17	4,9	39	199	+18	203	+28
30	300	7	5.57	4,2	34	202	+47	217	+56
31	400	6	5.07	5.4	32	119	+81	11	+80
32	200	6	4.78	4.1	38	163	+51	163	+19
33	500	6	5,36	7.8	26	13	+80	353	+69

TABLE 3.10

Derry Bay Felsite

Overall analysis

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							Palaeomagnetic Pole			
NRM - in situ	6	5.64	13.7	19	188	+61	5°N	345°E	22	29
NRM - dip corrected	6	5,65	14.2	18	207	+72	22°N	334°E	28	32
NRM - in situ omitting sites 31, 33	4	3,88	24.4	19	198	+51	3°S	335°E	17	26
NRM - dip corrected omitting sites 31,33	4	3,88	25.5	19	214	+61	10°N	326°E	22	28
A.F. cleaned - in situ	6	4.46	3.3	44	186	+41	13°S	345°E	33	54
A.F. cleaned - dip corrected	6	4,50	3.3	44	194	+53	2°S	339°E	42	60
A.F. cleaned - in situ omitting sites 31, 33	4	3,62	7,8	35	189	+15	28°S	341°E	19	36
A.F. cleaned - dip corrected omitting sites 31, 33	4	3.62	7.8	35	192	+28	21°S	338°E	21	38

TABLE 3.11.

Glensaul Ignimbrite

Site mean analysis - Total NRM

Site	N (specs)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
59	4	2,89	not significant					
60	5	3,96	4.0	45	308	+40	310	-19
61	6	3,84	not significant					
62	7	5,40	3,8	36	330	+77	333	+31
63	5	4,95	74,4	9	295	+61	327	+19
64	6	4,90	4,6	35	251	+69	302	+40
65	6	2,06	not significant					

Site mean analysis - A.F. cleaned

Site	Optimum field	N	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
59	200	4	3,27	4,1	52	200	+31	218	+63
64	300	7	5,51	4,0	34	187	-3	191	+27
65	200	5	4,32	5,9	34	207	-2	235	+43
60	300	5	3,83	3,4	49	9	+79	332	+22
61	500	6	5,60	12,4	20	352	+77	330	+18
62	300	5	3,92	3,7	46	40	+74	340	+25
63	300	5	3.78	18,3	18	323	+65	340	+15

TABLE 3.12

Glensaul Ignimbrite

Overall analysis

	N	R	k	α95	D	I	Lat. (Palaeomagnetic Pole)	Long. (Palaeomagnetic Pole)	dψ	dχ
NRM										
Five significant sites *in situ*	21	17.25	5.3	15	295	+65	49°N	279°E	20	24
dip corrected	21	16.30	4.3	18	317	+18	34°N	225°E	10	18
A.F. cleaned										
Seven significant sites *in situ*	7	4.68	2.6	47	309	+65	13°N	331°E	62	76
dip corrected	7	4.62	2.5	48	303	+47	43°N	252°E	41	63
Group A sites 59, 64, 65										
in situ	16 (samples)	12.37	4.1	21	197	+6	30°S	330°E	11	2[illegible]
dip corrected	16 (samples)	12.37	4.0	21	209	+43	8°S	323°E	16	2[illegible]
Group B sites 60, 61, 62, 63										
in situ	21 (samples)	17.89	6.4	14	353	+75	80°N	330°E	7	1[illegible]
dip corrected	21 (samples)	18.05	6.8	13	335	+20	43°N	205°E	7	1[illegible]

TABLE 3.13

The Upper Llandovery Keratophyre-Lough Nafooey

Total NRM - site mean statistics

Site	N (samples)	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
34	6	4.79	4.1	38	148	+63	132	+11
35	5	4.91	45.9	11	13	+59	105	+45
36	6	5.60	12.6	20	237	+64	186	+15
37	6	2.34	not significant					
38	6	5.09	5.4	32	339	+72	159	+49
39	6	4.39	3.1	45	358	+54	127	+56
40	5	4.95	72.4	9	356	+82	270	+30
41	7	6.61	15.5	16	135	+82	252	+35
42	6	5.79	24.0	14	359	+81	34	+3
43	7	6.89	55.1	8	354	+65	25	-6
44	6	5.28	7.0	27	271	+43	201	+23

TABLE 3.14

The Upper Llondovery Keratophyre - Lough Nafooey

A.F. cleaned - site mean statistics

Site	Optimum field	N (samples)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
34	600	6	5.46	9.2	23	32	+36	62	+18
42	300	6	5.82	27.0	13	333	+73	25	+4
43	300	6	5.91	55.9	9	353	+78	34	+2
36	300	6	5.76	21.1	15	230	+22	222	-9
40	300	5	4.93	55.1	10	329	+75	276	+24
44	300	6	5.66	14.5	18	260	+71	177	+13
38	300	5	4.55	8.9	28	271	+74	181	+28
35	300	5	4.04	4.2	43	156	+73	145	+14
39	300	6	5.20	6.2	29	6	+80	146	+34
37	300	6	2.99	not significant					
41	400	5	3.37	not significant					

TABLE 3.15

The Upper Llandovery Keratophyre - Lough Nafooey

Overall analysis

	N	R	k	α95	D	I	Lat.	Long.	dψ	dχ
							Palaeomagnetic Pole			
NRM										
in situ	10 (sites)	9.11	10.1	16	329	+80	69°N	322°E	29	31
dip corrected	10 (sites)	4.78	not significant							
A.f. cleaned (allowing for dual polarity)										
in situ	7 (sites)	2.44	not significant							
dip corrected	7 (sites)	5.79	5.0	30	35	-5	27°N	130°E	15	30
intermediate group										
in situ	11 (samples)	8.99	5.0	23	102	+86	51°N	3°E	45	45
dip corrected	11 (samples)	9.10	5.3	22	145	+25	18°S	26°E	26	48

TABLE 3.16

Salrock Group Sediments - Total NRM - Section 1

Site	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
(SILL)							
6	6	5.89	45,5	91	+57	66	-10
7	7	4.34	2.3	91	+62	61	-2
8	7	5.09	3,1	180	+76	38	+28
9	6	5.87	31,1	64	+26	69	-37
(SILL)							
12	6	5.68	15.5	89	+35	73	-10
13	7	6.95	127.4	72	+20	74	-24
14	7	6.13	6,9	133	+56	50	+40
15	6	5.87	3,9	355	+79	15	+22
(SILL)							
18	6	5.73	18.2	122	+67	39	+34
19	6	5.94	83.2	31	+74	16	+15
20	5	2,54		not significant			
21	6	5.69	16.1	113	+71	32	+29
22	5	3.30		not significant			
23	6	5.36	7.8	132	+23	100	+33
24	6	5.92	62.5	62	+43	52	+ 1
25	6	5.21	6.3	25	+30	26	-34
26	3	2.26		not significant			
27	5	4.97	143.9	32	+27	32	-25
28	7	5.55	4.1	35	+36	30	+ 6
29	4	3.37	4.7	116	+51	63	+30
30	6	5.76	20.9	51	+47	42	+ 2
31	7	6.22	7.6	49	+43	43	-4
32	6	3.77		not significant			
33	6	4.76	4,0	31	+48	24	-4
34	6	5.95	99,0	69	+30	54	-7
35	6	5.81	26,1	51	+43	36	-11
36	6	5.51	10.1	213	+55	340	+60
37	6	5.93	72.6	51	+51	34	+ 1
38	6	5.92	65.5	61	+31	51	-9
39	6	5.84	32,1	87	+52	45	+19
40	6	5.77	22,0	60	+16	63	-20
41	6	4,05	2,6	73	+ 7	81	-20

(Sites are listed in ascending stratigraphic order and the occurrence of igneous bodies is indicated)

TABLE 3.17

Salrock Group Sediments - Total NRM-Section 2

Site	N (specs)	R	k	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
(SILL)							
1	6	5,85	33,1	159	+78	29	+22
2	6	5,46	9,2	136	+59	53	+26
3	5	4,60	9,9	40	+52	29	-11
4	6	5.84	31,2	94	+44	72	+ 5
5	5	4,84	25,4	59	+39	50	-15
6	6	5,41	8,5	292	+76	356	+18
7	6	5,68	15.6	211	+85	10	+30
8	4	3,94	46,6	64	+33	58	-18
9	5	4.65	11,5	103	+56	53	+11
10	4	3.80	15,1	45	+58	31	-18
11	3	2,99	232,2	69	+33	63	-20
12	5	4,92	52.1	154	+78	20	+25
13	6	5,90	49.6	50	+73	24	+ 5
(SILL)							
16	5	4,83	23.4	61	+62	33	-1
17	5	4.84	25.0	63	+26	60	-19
18	6	5.62	13,2	64	+61	40	-5
19	6	5.92	61.6	62	+34	58	-26
20	6	5,89	45,7	81	+50	52	+ 1
21	6	5.52	10,3	38	+83	19	+13
(SILL)							

(sites listed is descending stratigraphic order)

TABLE 3.18

Salrock Group Sediments - Total NRM

Overall analysis

	N (sites)	R	k	D	I	Long. (palaeomagnetic pole)	Lat.	$d\psi$	$d\chi$
Section 1									
in situ	28	24,2	7,2	71	+49	75°E	35°N	10	14
dip corrected	28	24,5	7,8	49	+1	115°E	23°N	5	10
Section 2									
in situ	19	17,2	10,0	72	+61	63°E	43°N	13	17
dip corrected	19	17.1	9.4	40	+1	124°E	28°N	6	12
Combined									
in situ	47	41,22	8,0	72	+54	71°E	38°N	8	11
dip corrected	47	41.49	8,4	45	+1	119°E	26°N	4	8

TABLE 3.19

Intrusives and Baked Contacts of Upper Silurian age.- Killary Harbour

Site mean analysis - Total NRM

Site	N (specs)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
MICROGRANODIORITE								
MG1	7	2.73	2.7	not significant				
MG2	6	3.77	3.8	not significant				
MG3	6	3.90	2.4	56	330	+75	3	+28
MG4	6	4.85	4.4	23	253	+62	320	+54
MG5	7	6.36	9.4	21	141	+85	15	+48
MG6	6	5.86	35.5	11	351	+51	358	+ 7
MG7	6	5.37	8.0	25	242	+82	0	+50
MG8	7	6.23	7.7	23	15	+77	11	+33
MG9	6	5.87	39.2	11	309	+68	359	+36
ANDESITES								
SAL 1/4	9	6.92	3.8	30	258	+24	317	+49
contact	4	3.38	4.8	47	241	+37	348	+58
SAL 1/11	7	6.89	55.6	8	338	+64	6	-3
contact	7	6.36	9.3	21	258	+64	26	+48
SAL 1/43	6	5.88	42.5	10	15	+78	26	+19
contact	6	5.81	26.1	11	247	+18	282	+55
SAL 1/45	6	5.93	67.0	8	245	+69	344	+43
contact	6	4.07	2.6	40	207	+21	285	+68
SAL 2/23	6	2.32	1.4	not significant				
contact	6	5.56	11.4	21	261	+10	286	+22

TABLE 3.19 (continued)

Intrusives and Baked Contacts of Upper Silurian age - Killary Harbour

Site mean analysis - Total NRM

Site	N (specs)	R	k	$\alpha 95$	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
LAMPROPHYRES								
SAL 1/17	6	3.66	2.1	not significant				
contact	4	3.33	4.5	49	286	+48	332	+26
SAL 2/15	6	5.70	17.1	17	13	+82	358	+14
contact	5	4.77	17.2	19	230	+39	301	+40
SAL 2/48	7	5.29	3.5	38	308	+44	328	+ 0
SAL 2/49	7	6.80	30.1	11	205	+89	5	+31
SAL 2/50	7	6.90	57.3	8	315	+86	1	+27
SAL 2/52	7	6.93	89.7	6	290	+81	355	+27

TABLE 3.20

Intrusives and Baked Contacts of Upper Silurian age - Killary Harbour

Site mean analysis - A.F. cleaned

Site	Optimum field	N	R	k	α_{95}	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
MICROGRANODIORITE									
1	300	6	5.59	12.1	20	261	+57	316	+48
2	300	7	6.72	21.1	14	256	+30	283	+37
3	300	5	4.91	46.7	11	274	+17	291	+19
4	300	7	6.80	29.7	11	228	+48	317	+66
5	300	6	5.49	9.7	23	256	+61	327	+49
6	500	6	4.61	3.6	41	338	+58	353	+16
7	500	6	5.12	5.7	31	234	+44	294	+59
8	300	6	5.60	12.6	20	290	+68	342	+39
9	300	6	5.90	50.7	10	268	+60	328	+44
ANDESITES									
SAL 1/4	200	7	5.32	3.6	37	262	+3	290	+40
contact	400	3	1.85	not significant					
combined		10	6.90	2.9	29	252	+5	288	+49
SAL 1/11	200	7	6.74	22.8	13	306	+62	356	+9
contact	200	6	5.15	5.9	30	259	+39	348	+61
combined		13	11.29	7.0	17	280	+55	354	+31
SAL 1/43	600	7	5.32	3.6	37	249	+43	332	+59
contact	100	7	6.88	48.3	9	244	+11	272	+52
combined		14	11.69	5.6	19	246	+25	295	+58
SAL 1/45	500	7	6.57	14.1	17	227	+4	247	+43
contact	100	8	7.83	41.5	9	229	+19	266	+50
combined		15	14.28	19.5	9	228	+12	257	+47
SAL 2/23	200	6	4.90	4.5	35	257	-14	255	+16
contact	100	5	4.90	40.2	12	263	+4	280	+18
combined		11	9.60	7.1	18	260	-5	267	+17

TABLE 3.20 (continued)

LAMPROPHYRES

Site	Optimum field	N	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
SAL 1/17	300	6	4.09	2.6	52	272	+35	311	+33
contact	300	4	3.75	11.9	28	249	+23	291	+46
combined		10	7.67	3.9	28	261	+30	302	+40
SAL 2/15	300	6	4.81	4.2	37	226	+58	315	+47
contact	100	6	5.83	29.2	13	226	+31	293	+43
combined		12	10.54	7.5	17	226	+44	302	+46
SAL 2/48	400	5	3.75	3.2	51	240	+22	260	+36
SAL 2/49	200	7	6.44	10.8	19	225	+39	301	+56
SAL 2/50	300	6	5.25	6.6	28	223	+73	350	+43
SAL 2/52	300	5	4.58	9.5	26	240	+21	280	+35

TABLE 3.21

Intrusives and Baked Contacts of Upper Silurian age - Killay Harbour

Overall analysis

Unit weight to each site

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							Palaeomagnetic pole			
MICROGRANODIORITE										
NRM										
in situ	9	7.77	6.5	22	298	+85	57N	334E	43	43
dip corrected	9	7.79	6.6	22	5	+43	61N	161E	17	27
A.C. CLEANED										
in situ	9	8.24	10.6	17	263	+53	23N	286E	16	23
dip corrected	9	8.28	11.0	16	318	+44	48N	236E	13	20
ANDESITES										
NRM										
in situ	9	7.46	5.2	25	252	+48	13N	292E	21	32
dip corrected	9	7.34	4.8	26	339	+48	61N	209E	22	34
A.C. CLEANED										
in situ	9	7.91	7.4	20	252	+20	2S	281E	11	21
dip corrected	9	7.49	5.3	25	290	+46	33N	262E	20	31
LAMPROPHYRES										
NRM										
in situ	7	6.37	9.5	21	280	+72	47N	298E	31	36
dip corrected	7	6.48	11.5	19	344	+25	48N	194E	11	20

TABLE 3.21 (continued)

Intrusives and Baked Contacts of Upper Silurian age - Killay Harbour

Overall analysis

Unit weight to each site

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							Palaeomagnetic pole			
LAMPROPHYRES (continued)										
AC CLEANED										
in situ	8	7.49	13,6	16	240	+38	1N	296E	11	18
dip corrected	8	7.54	15,2	15	299	+45	38N	254E	12	19

TABLE 3.22

Intrusives and Baked Contacts of Upper Silurian age - Killay Harbour

Overall Analysis

Combining dykes and contacts - A.F. Cleaned

	N (sites)	R	k	α_{95}	D	I	Lat. (Palaeomagnetic Pole)	Long. (Palaeomagnetic Pole)	$d\psi$	$d\chi$
ANDESITES										
In situ	5	4.44	7.1	31	257	+19	1°N	276°E	17	32
dip corrected	5	4.35	6.1	34	293	+43	33°N	258°E	26	42
LAMPROPHYRES										
In situ	6	5.62	13.3	19	239	+38	1°N	297°E	13	23
dip corrected	6	5.59	12.3	20	298	+46	38°N	256°E	16	25

TABLE 3.23

Intrusives and Baked Contacts at Upper Silurian age - Killary Harbour

Final analysis - A.F. cleaned

	N (sites)	R	k	α_{95}	D	I	Lat	Long	$d\psi$	$d\chi$
							Palaeomagnetic pole			
Andesites and Lamprophyres combined										
in situ	11	9.83	8.5	17	248	+30	1°N	287°E	10	18
dip corrected	11	9.93	9.4	16	296	+45	36°N	257°E	13	20
Andesites, Lamprophyres and microganodiorite combined										
in situ	20	17.63	8.0	12	254	+41	9°N	286°E	9	15
dip corrected	20	18.03	9.7	11	306	+45	42°N	248°E	9	14

TABLE 3.24

Knocknaveen Group, Louisburgh

NRM - site mean statistics

					in situ		dip corrected	
	N	R	k	α_{95}	D	I	D	I
1	8	7.67	21.3	12	346	+84	144	+67
2	6	5.88	42.7	10	41	-50	27	-44
3	5	4.72	14.4	21	187	-16	57	-59
4	6	5.71	17.1	17	186	-70	31	-24
5	5	4.89	35.0	13	246	-69	356	-47
11	6	5.94	83.4	7	122	+33	56	+9
12	6	5.88	42.8	10	149	+39	36	+22
13	6	5.80	25.6	14	131	+5	77	+30
14	6	5.63	13.6	19	144	+13	61	+37
15	5	4.76	16.8	19	169	-17	66	-72
16	4	3.67	9.0	33	180	-37	17	-62
17	6	5.50	10.1	22	197	-26	333	-71
18	6	5.63	13.6	19	209	-6	268	-67

Overall analysis

	N (Sites)	R	k	α_{95}	D	I	Lat. Palaeomagnetic Pole	Long.	$d\psi$	$d\chi$
in situ	13	7.34	2.1	39	165	-15	42S	9E	20	40
dip corrected	13	7.44	2.2	38	41	-31	11N	130E	23	43

TABLE 4.1

The Kildare Inlier

Total NRM - site mean statistics

Site	N (specs)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
67	6	2.36	1.4	not significant				
68	5	4,56	9.1	27	176	+27	182	-13
69	6	5.93	69.0	8	111	+28	165	+37
70	6	3,99	2.5	54	196	-2	176	+18
71	6	4,35	3.0	46	117	46	178	+36

A.f. cleaned - site mean statistics

Site	Optimum field	N (specs)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
67	300	7	6.77	26.0	12	130	+40	173	+26
68	100	5	4.55	8.9	27	174	+31	184	-9
69	100	6	5.91	56.4	9	111	+29	155	+38
70	300	6	5.85	32.3	12	111	+47	178	+41
71	300	7	6,90	60.4	8	111	+61	195	+40

TABLE 4.2

The Kildare Inlier

Overall Analysis

	N (sites)	R	k	α_{95}	D	I	Lat.	Long	$d\psi$	$d\chi$
							Palaeomagnetic pole			
NRM *in situ*	5	3.32	not significant							
NRM dip corrected	5	3.32	not significant							
A.F. cleaned *in situ*	5	4.64	11.1	24	129	+44	1°N	38°E	19	30
A.F. cleaned	5	4.64	11.1	24	177	+28	21°S	356°E	14	26

TABLE 4.3

Balbriggan, and Portrane Inliers

TOTAL NRM - site mean analysis

SITE	N (specs)	R	k	α95	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
BALBRIGGAN								
1	5	4.84	24,4	16	257	-38	258	+7
2	5	4.06	4,3	42	233	+12	217	+50
3	5	4,09	4,4	41	198	+36	159	+36
4	5	4.30	5.7	35	256	+29	219	+20
5	3	2.73	7,5	49	200	+61	131	+36
6	5	3,62	2,9	55	176	+61	150	+16
7	6	4,89	4,5	36	209	-18	236	-24
8	6	5,06	5,3	32	186	-13	224	-36
9	5	4,48	7,7	29	231	+74	174	+40
10	6	5.72	17,6	16	302	+82	161	+52
11	6	5,06	5,3	32	218	+20	212	-3
12	3	2,79	9,3	43	225	+44	201	+19
13	6	4.12	2,7	51	217	+4	222	-16
SHENICK'S ISLAND								
14	6	5.35	7,7	26	340	+88	168	-13
15	4	3,56	7,3	36	187	+43	187	-44
PORTRANE								
17	6	4,28	2,9	48	250	+49	162	+73
18	5	3,84	3,5	48	231	+5	218	+35
19	6	4,39	3,1	46	164	+78	110	+17
20	6	5.78	22,9	14	143	+41	130	+6
21	6	0.61	not significant					
22	6	5.36	7,8	26	177	+40	151	+23
23	6	5,55	11,1	21	185	-14	193	-6
24	6	5.57	11,6	21	210	+53	139	+49
25	6	4.31	3.0	47	281	+75	192	+60

TABLE 4.4

Balbriggan and Portrane Inliers

A.F. Cleaned - site mean statistics

Site	Optimum Field	N	R	k	α_{95}	D (in situ)	I (in situ)	D (dip corrected)	I (dip corrected)
BALBRIGGAN									
1	500	5	4,91	45,0	12	297	-53	282	-13
2	300	5	4,86	29,4	14	237	-57	247	-14
3	400	6	5.39	8,2	25	197	+23	174	+28
4	300	4	3,75	11,9	28	208	-41	244	-33
5	unstable upon demagnetization								
6	unstable upon demagnetization								
7	200	6	5,58	12.0	20	206	-46	252	-35
8	300	6	4,82	4,2	37	201	-19	222	-22
9	NRM	5	4,48	7,7	29	231	+74	174	+40
10	NRM	6	5,72	17,6	16	302	+82	161	+52
11	200	6	4,54	3,4	43	203	+17	202	-13
12	200	2	insufficient data for analysis						
13	unstable upon a.f. demagnetization								
SHENICKS ISLAND									
14	NRM	6	5,35	7,7	26	340	+88	168	-13
15	unstable upon af. demagnetisation								
PORTRANE									
17	300	6	5,32	7,4	27	224	+19	202	+31
18	100	6	5.62	13,1	19	228	-14	227	+17
19	300	6	4.59	3,6	42	193	-5	196	+7
20	200	6	5,96	119,5	6	146	+27	139	-4
21	200	6	5.88	41.7	11	145	+72	71	+54
22	400	6	5,77	21,7	15	192	0	190	+5
23	200	6	5.78	23,1	14	174	-28	196	-23
24	400	5	4,69	12,8	22	221	+21	195	+40
25	300	6	5,76	21,2	15	226	-44	246	-8

TABLE 4.5

Overall Analysis

BALBRIGGAN AND SHENICK'S ISLAND

	N	R	k	α_{95}	D	I	Lat. Palaeomagnetic	Long pole	$d\psi$	$d\chi$
NRM										
<u>in situ</u>	15	11,28	3,8	23	217	+36	10S	319E	15	27
dip corrected	15	10,81	3,3	25	196	+12	28S	335E	13	25
a.f. cleaned										
<u>in situ</u>	10	4,99	not significant							
dip corrected	10	6,76	2,8	36	214	-4	31S	313E	18	36

PORTRANE

	N	R	k	α_{95}	D	I	Lat.	Long	$d\psi$	$d\chi$
NRM										
<u>in situ</u>	8	6,22	3,9	32	201	+48	5S	336E	28	42
dip corrected	8	6,14	3,8	33	150	+38	10S	22E	23	39
a.f. cleaned										
<u>in situ</u>	9	6,84	3,7	31	199	-11	39S	329E	16	32
dip corrected	9	6,91	3,8	30	203	+2	32S	326E	15	30

TABLE 4.6

The Grangegeeth Volcanics

Total NRM - site mean analysis

Site	N (specs)	R	k	α95	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
26	5	4.95	77.2	9	173	+70	191	+46
27	6	5.89	44.9	10	225	+56	222	+27

a.f. cleaned - site mean analysis

Site	Optimum field	N (specs)	R	k	α95	D (*in situ*)	I (*in situ*)	D (dip corrected)	I (dip corrected)
26	100	6	5.70	16.5	17	174	+46	186	+21
27	400	6	5.97	134.1	7	187	+57	199	+31

Overall analysis

	N (specs)	R	k	α95	D	I	Lat (palaeomagnetic pole)	Long (palaeomagnetic pole)	dψ	dχ
NRM										
in situ	11	10.56	22.9	10	208	+65	13°N	334°E	13	16
dip corrected	11	10.56	22.9	10	212	+35	11°S	324°E	7	11
A.F. cleaned										
in situ	12	11.58	25.9	9	180	+52	4°S	354°E	8	12
dip corrected	12	11.58	25.9	9	193	+26	22°S	340°E	5	9

TABLE 5.1

Lower Paleozoic and Devonian data from the British Isles

	Age	N	k	α_{95}	D	I	Lat (°N)	Long (°E)	dψ (A95)	dχ
1 CAERFAI SERIES	Є1-Єm	16 sites	21*	9	185	+23	26	169	6	10
2 CARISP PORPHYRY	Єm	16 sites	4	22	26	-1	28	146	11	22
3 BALLANTRAE VOLCANICS	Ol	12 samples	-	10	189	+40	11	168	(10)	
4 YOUNGER GABBROS ABERDEENSHIRE	Ol-m	32 sites	10	9	168	+34	11	189	6	10
5 EYCOTT GROUP, LAKE DISTRICT	Ol	29 sites	22	6	0	-43	10	176	5	7
6 BORROWDALE GROUP LAKE DISTRICT	Ol-m	12 sites	20	10	338	-46	6	196	8	13
7 CARROCK FELL COMPLEX	O(u?)	17 sites	13	10	351	-29	19	184	6	11
8 DIORITE DYKE, STILE END, LAKE DISTRICT	O(u?)	12 samples	6	20	5	-53	2	173	19	27
9 BUILTH VOLCANIC SERIES	Ol	15 sites	19	9	177	+39	16	179	6	11
10 MINOR-INTRUSTIONS OF ASHGILIIAN AGE, BUILTH	Ou	6 sites	37	11	174	+55	2	2	11	16
11 TREFGAN ANDESITIC SERIES	Ol	7 sites	10	20	183	+53	5	172	19	27
12 FISHGUARD VOLCANIC SERIES	Ol	9 sites	5	25	61	-34	2	119	16	28
13 CONNEMARA GABBROS	Єu-OL	20 sites	22	7	227	+31	9	125		11°

TABLE 5.1 (continued)

Lower Paleozoic and Devonian data from the British Isles

	Age	N	k	α95	D	I	Lat (°N)	Long (°E)	dψ	dχ (A95)
14 SOUTH CONNEMARA SERIES	Ol	6 sites	3	46	5	+9	42	164	24	47
15 LOUGH NAFOOEY SPILITES	Ol	15 sites	6	18	4	+10	42	165	9	18
16 MWEELREA IGNIMBRITES	Ol	17 sites	6	20	131	+27	11	218	10	18
17 GLENSAUL FELSITE	Ol	16 samples	4	21	197	+6	8	143	16	26
18 DERRY BAY FELSITE	Ol	4 sites	8	35	192	+28	21	158	21	38
19 CHAIR OF KILDARE	Ou	5 sites	11	24	177	+28	21	176	14	26
20 GRANGEGEETH	Ou	12 samples	26	9	193	+26	22	160	5	9
21 PORTRANE	Ou	9 sites	4	30	203	+2	32	146	15	30
22 BALBRIGGAN and SHENICK's ISLAND	Ou	10 sites	3	36	214	-4	31	133	18	36
23 LAMBAY ISLAND	Ou	7 sites	84	7	145	-25	42	221	-	-
24 SKOMER VOLCANIC GROUP	Ou(-Sl)	10 sites	9	17	196	49	32	154	-	-
25 KLANDOVENY TRAPS TORTWOTH INLIER	Sl	11 samples	12	14	261	+34	9	287	9	16
26 BASAL KERATOPHYRE, LOGUH NAFOOEY	Sl	8 sites	5	28	40	-10	23	127	15	29
27 SALROCK GROUP	Su	47 sites	8	8	45	+1	26	119	4	8
28 INTRUSIVES into UPPER OWENDUFF and SALROCK FORMATIONS	Su-Dl	20 sites	8	12	254	+41	9	286	9	15

TABLE 5.1 (continued 3.)

Lower Paleozoic and Devonian data from the British Isles

	Age	N	k	α95	D	I	Lat (°N)	Long (°E)	dψ dλ (A95)
29 KNOCKNAVEEN GROUP, LOUISBURGH	Su	13 sites	2	38	41	-31	11	130	23 43
29 (a) KNOCKNAVEEN GROUP LOUISBURGH	Su	4 sites	4	31	34	-54	3	323	31 44
30 GARABAL HILL-GLEN FYNE COMPLEX	Su-(Dl)	5 sites	11	24	32	-43	5	146	18 30
31 ARROCHAR COMPLEX and AUREOLE	Su-(Dl)	6 sites	167	5	213	+37	8	144	4 6
32 FOYERS GRANITE	Ol?-Dl?	23 sites	4	18	14	-6	29	160	9 18
33 LAVAS of lower ORS age and associated baked sediments, MIDLAND VALLEY	Su-Dl	34 sites	12	7	40	-39	5	140	5 9
34 LAVAS of lower ORS age, LORNE PLATEAU	Su-Dl	5 sites	23	17	66	-25	2	112	10 18
35 LAVAS of lower ORS age, GLENCOE	Su-Dl	11 sites	19	11	36	-54	6	329	10 15
36 LAVAS of lower ORS age and associated baked sediments SCOTLAND	Su-Dl	50 sites	13	6	41	-40	4	140	4 7
37 CHEVIOT HILLS lavas	Dl	11 sites	10	15	49	-53	11	320	(18)
38 LOWER OLD RED SANDSTONE SEDIMENTS	Dl(u)	35 samples	5	13	66	-38	2	298	12 14
39 LAVAS of ORS age ORKNEY AND SHETLANDS	Dm-u	7 specs.	45	9	205	+8	24	150	-

TABLE 5.1 (continued 4.)

Lower Paleozoic and Devonian data from the British Isles

40 LAVAS of ORS age ORKNEY and SHETLANDS	Dm-u	7 sites	18	14	216	+46	2	327	12	18
41 UPPER ORS sediments JEDBURGH	Du	10 samples	7	9	188	+22	23	169	5	9
42 UPPER ORS and LOWER CARBONIFEROUS LIMESTONE, BRISTOL DISTRICT	Du-Cl	10 sites	23	10	196	+9	32	158	5	10

underlined numbers are principal data.

TABLE 5.2

ANOMALOUS RESULTS

Overall analysis - a.f. cleaned

	N	R	k	α_{95}	D	I	Lat.Long		$d\psi$	d
(1) Borrowdale Volcanic Group										
In situ	8 (sites)	7.43	12.3	16	337	+80	71N	334E	30	3
dip corrected	8 (sites)	7.31	10.2	18	284	+73	50N	305E	29	3
(2) Dykes intruding the Eycott Group										
In situ	6 (sites)	5.80	24.6	14	25	+58	67N	120E	15	2
dip corrected	6 (sites)	5.80	24.6	14	14	+66	80N	116E	19	2
(3) Mweelrea ignimbrite - Band 3										
In situ	6	3.67	not significant							
dip corrected	6 (sites)	4.18	2,8	50	318	+18	19N	315E	27	5
(4) Glensaul Felsite										
In situ	21 (specs)	17.89	6,4	14	353	+75	80N	330E	23	2
dip corrected	21 (specs)	18.05	6,8	13	335	+20	43N	205E	7	1

TABLE 5.3

Borrowdale Volcanic Group - NRM

SITE	N	R			k		
		R_{Holes}	R_{Cores}	$R_{in\ situ}$	k_{holes}	k_{Cores}	$k_{in\ situ}$
4	7	6.30	6.45	6,92	9,1	10.8	78,5
5	6	5,18	4,27	4.11	6,1	2,9	2.4
6	5	4.33	2,00	3,88	6,0	1.3	3,6
7	7	6,08	4,70	5.20	6,5	2.6	3,3
8	5	4.12	2.61	1,52	4,6	1.7	1,1
9	5	4,51	4.46	4,88	8,2	7.4	34.4
10	6	5.77	2,22	4,66	22,0	1.3	3.7
11	7	6.28	6,39	6,63	8.3	9.9	16.3
69	5	4,49	4,66	4.87	7.7	11,9	29,8
70	7	6,51	6.46	6,76	12,2	11.2	24,5
71	6	5.55	5,65	5.46	11,1	14.3	9,3
72	6	4,90	3,97	4.13	4.6	2,5	9,3
73	7	5,88	5.40	5.74	5,4	3.8	3.8
74	7	5,39	3.78	5,99	3.7	1,9	6.0
75	5	4,83	4.16	3.63	23.9	4.7	2.9
76	6	5,23	5,66	5,95	6.5	14.6	94.6
77	7	6,87	6,72	6.93	47.0	21.4	85,9
78	6	4,47	4,62	4.33	7,6	10.7	5.9
79	6	5.72	5.87	5.93	18.0	39,6	74,1
80	6	5,94	5,00	5,29	85,4	5,0	7,0
81	6	5.56	4,31	5,46	11,2	3,0	9.3
82	5	4.84	4,89	4,71	26.4	34.7	13,6
84	6	5,59	5,67	5,20	12,1	15.1	6.3